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PREFACE

This publication contains papers presented at the ARS Conference on Hydrology held in Denver, Colorado, September 13-15, 1993. The purpose of the conference was to assess the status of hydrology research in ARS, identify promising new technologies and research areas, develop a strategy for future research, and identify and develop new leadership for the ARS hydrology program.

ARS hydrologic research began over four decades ago. The early phase of the program was devoted to the selection, development, and instrumentation of experimental watersheds. The watersheds were envisioned as outdoor laboratories that could be used to provide data for determining the effects of various management practices on hydrologic response, developing hydrologic design criteria, and other applications. The data bases that have resulted from the experimental program have been used extensively by ARS scientists and engineers, as well as professionals in government, academia, and the private sector. In addition to the original purpose, the watershed data have been used to test hydrologic theories, evaluate land treaments, validate hydrologic models, and many other applications. The technology and data that have resulted from the ARS program have also proven to be invaluable in assessing agricultural related non-point source water quality problems. Without the early commitment and vision of the ARS scientists and engineers that pioneered the development of the ARS hydrology research program, these accomplishments would not have been possible.

Many of the scientists that laid the foundation of the ARS hydrology program and conducted the initial research have retired or will retire within the next few years. It is important that the program continue to prosper so that the infrastructure that is in place will continue to be available to address current and future hydrology-related environmental issues. To ensure this continuity, it is imperative that the program for the future be charted and that the responsibilities for technical leadership of the program be shifted to the next generation of the program's professional staff. The ARS Conference on Hydrology was designed to facilitate development of future leadership of the program by providing a broader perspective of the program to the participants, by identifying current issues related to the science of hydrology and watershed management, and by assessing the utility of new technology developed in other fields for application to hydrology. To accomplish this the participants were divided into teams and asked to develop position papers on specific topics. The assigned topics ranged from assessing the status and future utility of the ARS experimental watersheds to the application of new theory such as Chaos Theory and recently developed tools such as Geographic Information Systems. The papers contained herein are the results of the collective efforts of the participants. In addition to providing continuity to the ARS hydrology program, the individual papers contained within this Proceedings should be a valuable resource for others conducting hydrologic research.

Clarence Richardson
Proceedings Editor

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The ARS Conference on Hydrology was developed under the leadership and direction of Dr. David A. Farrell, National Program Leader for Hydrology and Remote Sensing. Members of the Editoral Committee were:

Clarence Richardson, Chair
Albert Rango
Lloyd Owens
Leonard Lane

Members of the Publications Committee were:

Ross Wight, Chair
Frank Schiebe
Adrian Thomas
Harry Pionke

The biographical information for the conference participants was prepared by Virginia Ferreira and the post-conference program was organized by Frank Schiebe.

Land-Atmosphere Interactions

M.S. Seyfried[1], W.P. Kustas[2], G.L. Johnson[3], and C.M. Feldhake[4]

Summary

In this report we discuss issues that are of potential importance to ARS hydrology personnel in terms of future research. Recent developments in remote sensing technology and computer science provide us with the possibility of linking the major components of the soil-plant-atmosphere system for the first time. We have focused on water and energy fluxes, leaving gaseous and chemical fluxes to others. Three major areas of study were identified: (i) development of alternative verifiable modeling techniques that are based on known physical processes, (ii) use of remote sensing and atmospheric data to improve estates of large-scale water and energy fluxes, and (iii) application of these approaches to heterogenous landscapes that include different kinds of land use and/or topography. Critical knowledge gaps in these topics are generally related to the discrepancies of scale encountered between newly developed technologies and previous work. These gaps were described in the text and specific topics of research presented that address those gaps.

Introduction

There has been great interest in land-atmospheric interactions at least since the 1700's when it was discovered that plants obtained CO_2 from the atmosphere and produced O_2. Certainly it has been relevant to agricultural sciences since then. There has been an important shift in emphasis lately, however. Previous work was generally performed on a small scale, either in a controlled laboratory or small plot environment. For these studies the atmosphere was an independent, outside influence which provided inputs to the soil-plant system and received outputs from that system, but was essentially unchanged by it. Thus, there was considerable study of arrows 1, 2, 3 and 4 in Figure 1. It is well established that the atmosphere (climate) has an enormous impact on vegetation and soil development, and interactions between soil and vegetation are also well documented.

More recent studies have been conducted concerning arrows 5 and 6 (Fig. 1). This has been spurred by a number of societal and scientific developments. Increases in human population and technology development are resulting in increasingly large human impacts to our environment. In addition to the much discussed planet-wide changes in the atmospheric gasses which may affect global climate (Burke et al. 1991), there are instances of local activity by man changing local climate. Removal of vegetation by depletion of soil fertility, overgrazing, and collecting for fuel has produced desert-like landscapes that result in decreased precipitation which in turn causes decreases in biomass production (Glantz 1977, Sagan et al. 1979). Conversely, regions with major

[1] Soil Scientist, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[2] Hydrologist, USDA-ARS, Building 265, BARC-West, Beltsville, MD 20705.
[3] Meteorologist, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[4] Soil Scientist, USDA-ARS, P. O. Box 867, Beckley, WV 25802.

agricultural development through increased water availability using irrigation have, under some circumstances, experienced increased rainfall (Barnston and Schickedanz 1984, Lanicci et al. 1987).

Arrows 5 and 6 (Fig. 1) represent, among other things, ways in which humans affect their environment through alteration of the land surface. On the scientific front, the development of satellite monitoring technology and computer systems capable of interpreting satellite-derived data and integrating it with other landscape information, along with increasingly sophisticated simulation techniques, have made possible the study and quantitative estimation of fluxes represented by arrows 5 and 6 (Fig. 1). These developments provide very exciting possibilities for research and the advancement of our understanding of nature because they offer the potential to "close the loop." That is, we may be able to account for all six arrows in Figure 1.

A common thread running through all the scientific challenges and research opportunities related to land-atmosphere interactions is the difficulty of interpreting previously established knowledge of processes at a small scale in terms of more recently developed, large-scale measurements. Viewed from a small-scale perspective, landscape features such as soil type or geology, or plant characteristics such as leaf age or orientation, are known to have pronounced effects on infiltration and evapotranspiration. The question is, how can these effects be accounted for in a framework that may cover 10^2 km and includes 10^3 to 10^4 different soils and plants? This question becomes even more difficult with the inclusion of such obviously impacting features as mountains or urban areas. Viewed from the large-scale perspective, it seems clear that large-scale measurements are required to address regional and/or global questions. The problem is that current measurements on their own are rarely sufficient to quantify hydrologic processes of interest. The question then becomes, how can these large scale measurements be linked to known hydrological processes which have traditionally been studied at relatively small scale? These questions of scale are considered by some to be the most pressing problems facing hydrology today (Dooge 1982).

Our intent in this paper is to recommend a future role of the ARS in hydrologic studies related to land-atmosphere interactions. Our opinion is that the ARS should build future work on current strengths in terms of facilities and knowledge base as much as possible. One of our greatest assets is our physical resource base of experimental watersheds. These enable us to make long-term, detailed measurements of relevant land and atmospheric phenomena. The ARS maintains over 30 experimental watersheds in the continental U.S. ranging in size from 0.2 ha to 637 km^2. They cover most climatic regions of the country and are well instrumented (Thurman and Roberts 1993). Their value and interest as sites for investigating the application of remote sensing for computing large scale energy and water fluxes is evident from the recent field experiments conducted in the Walnut Gulch Watershed (Monsoon '90), in the Mahantango Watershed (MAC-Hydro-90) and in the Little Washita Watershed (Washita '92). Our knowledge base includes experimental scientists and modelers working on plant, soil and atmospheric processes at the laboratory to watershed scales.

Given these considerations, we have selected the following three major areas of promising future research: (i) modeling and parameterization of the land surface, (ii) measurement and parameterization of water and energy fluxes, and (iii) characterization of large-scale heterogeneities. A brief introduction to each topic which identifies current knowledge gaps follows below. These will be summarized in three scientific challenges we face. Specific research opportunities for ARS personnel follow those challenges.

Modeling and Parameterization of the Land Surface

Modeling, particularly at large scales (i.e., regional and global), will be an important area of research in hydrology in the coming years for both scientific and social reasons. Eagleson (1986) has gone so far as to state that, "He who controls the future of global-scale models controls the direction of hydrology." Modeling is a means of spatial and temporal extrapolation and interpolation of measured data and provides a forum for the testing of new hydrologic concepts. It is clearly an area of high potential impact due to the high societal interest and rapidity of emerging technologies. It is also an area of potential rapid breakthrough.

This discussion is largely limited to land-surface modeling due partly to the authors' expertise and partly because the conflicts between small-scale and large-scale approaches are especially acute at the land surface. This discussion focusses on basic soil and plant parameterization issues as opposed to how large-scale heterogeneities are addressed, which is discussed in a different section.

There have been a number of recent studies that have shown that there is considerable impact of land surface conditions on the atmosphere and ultimately on upper atmosphere circulation and climate. With regards to precipitation, Lanicci et al. (1987) concluded that soil-water content distribution in the Great Plains and Northern Mexico significantly affects convective storm evolution and Elfatih et al. (1992) estimated that 25% of the rainfall in the Amazon basin is derived from within basin evaporation. In other modeling studies Lee et al. (1991) found that horizontal variations in the landscape such as might result from land use changes, can result in local wind circulations that can be as strong as sea breezes in tropical and mid-latitude summer locations. A recurring issue involves the incorporation of small-scale land surface processes into relatively large-scale models (Avissar and Pielke 1989).

Currently there are numerous mesoscale atmospheric models in use. Henderson-Sellars et al. (1993) recently described 25 examples (although some are updates). Interestingly, the conceptual approach of all these models is similar. In fact, they are all based on the conceptual approach used in one-dimensional, point models developed in soil science about 20 years ago (eg., Nimah and Hanks 1973). Briefly, fluxes within the soil-water-plant-atmosphere continuum are conceived as driven by potential differences modulated by intervening resistances. There is some question as to how this conceptualization applies to large-scale models, however. Soil-water content, for example, is a critical land surface parameter that is difficult to model at large scales using the potential-resistance approach. It affects albedo, heat capacity, thermal conductivity, soil infiltrability, and the rates of evaporation and transpiration (McCumber and Pielke 1981). Others have noted that water and energy balance are sensitive to soil-water storage (Avissar 1992).

The basic equation used to calculate soil-water movement in soils is based on Darcy's equation which can be written:

$$q = K(W)(\partial h/\partial z - 1) \tag{1}$$

where q is the soil-water flux, W is the volummetric soil-water content, h is the soil-water potential, z is depth, and K is the hydraulic conductivity. The soil-water potential gradient drives soil-water movement and is related to W via a functional relationship known as the soil-water characteristic,

$$W = f(h) \tag{2}$$

which is unique to different soils. In addition, the K(W) relationship is highly variable and unique to different soils. Both functions are highly nonlinear.

Equation 1 has been tested and validated for small-scale laboratory studies but its application, even to small field plots is not assured because soil structural inhomogeneities (eg., macropores) may result in small-scale (cm) flow deviations (Beven and Germann 1982, Wilson et al. 1990). Thus the universal application of Eq. 1 is by no means accepted.

If, however, the appropriateness of Eq. 1 is accepted for large scale processes, there must be some way of evaluating an "average" h of an area that may include rivers, swamps, dry ridges and rock outcrops. It is clearly unmeasurable given current technology. If such a landscape property does exist we must then determine K(W) and h(W) functions. These are both highly variable in space and difficult to measure even at a small plot scale. In short, the physical meaning of Eq. 1 when applied to large scale is questionable at best. In addition, large scale models based on that equation are essentially unverifiable.

The problems associated with simulating plant uptake are similar to those concerning soil-water movement. Transpiration is largely controlled by a stomatal resistance term which is recognized as representing a lump sum of integrated stomatal resistance for the canopy and the bulk boundary-layer resistance for the canopy leaves. It is essentially unmeasurable at large scales. Some studies at smaller scales have concluded that the approach is not feasible (Ham and Heilman 1991). It is also strongly affected by h, which must be accurately simulated for the entire root zone, the extent of which is generally determined by "... intelligent guessing" (Henderson-Sellers et al. 1993). In addition, extensive parameterization is required. The Simple Biosphere model developed by Sellars et al. (1986), for example, requires 49 empirical constants. As with the case for soil-water movement, the theoretical foundation for transpiration simulation at large scale has been questioned and verification seems impossible.

Large scale heat flux simulation is plagued by the same types of problems. Surface heterogeneities, even at very small scale, can lead to dramatic fluctuations in surface temperature (Avissar 1992). These are not easily measured (Kustas et al. 1989). In addition, heat flux measurements depend on accurate characterization of surface cover, soil-water content and soil thermal properties such as thermal conductivity and heat capacity. As with other soil properties, the thermal properties vary considerably with soil and are not easily measured, even at a small plot scale. Thus, the problems associated with soil water movement and transpiration are added to measurement and characterization problems specific to heat flux.

Similar problems are associated with other surface properties. They may be summarized as problems related to: (i) interpretation of model parameters in terms of theory used to derive them at the scale of application, (ii) determination of all the parameter values required (even for a small scale), and (iii) true validation of the models.

These problems are appreciated by some in the field. We identify three major approaches that are being used to address them. The first is inverse modeling. In this approach the fundamental equations currently in use are assumed to be valid and the correct values of surface properties are determined from what they must be to obtain observed responses. Given the scale and measurement problems associated with soil water movement, transpiration, heat flux, and other surface properties that we have not included, it is probably proper to consider the "scaled up" values to be parameters rather than actual physical properties. This approach has had some success and there is no question

that is will have a role to play. Feddes et al. (1993) found that "...small-scale soil physics may describe large-scale hydrological behavior adequately , and effective hydraulic parameters concerned may be derived by an inverse modelling approach." This approach is also supported by Schmugge and Becker (1991).

A second approach is statistical-dynamical approach proposed by Avissar (1992) in which the most important characteristics of the soil-plant-atmosphere system that affect the partition of energy (e.g., plant stomal conductance, soil humidity, surface roughness) are represented by a probability density function rather than by a single "representative" value. This approach has not been used much but has a number of advantages. In particular, it acknowledges spatial variability but does not abandon important physical laws. Application will require determination of a number of probability distribution functions.

A third approach is to experimentally (and by simulation) build up our current, small scale knowledge to larger scales. This is alluded to as a hierarchical approach by Moran and Jackson (1991). Wood and Lacksmi (1993) have shown that this may be quite straightforward in some cases. They were able to "scale up" by simple linear aggregation. Examples of field scale experimental research includes that of Parlange et al. (1993) for the measurement of field scale soil-water diffusivity and Katul and Parlange (1993) for the measurement of field-scale soil temperature. Working along these lines Brutsaert (1986) suggests that use of atmospheric measurements, which integrate over larger surface areas, be employed to address larger-scale parameterization questions.

Measurement and Parameterization of Water and Energy Fluxes with Emphasis on Remote Sensing

Quantifying the water and energy fluxes from local to regional scales, and ultimately to global scales, necessitates the use of remote sensing technology. The primary reason for this is that remote sensing is the only tool available that can provide spatially distributed information. In addition, many weather satellites can provide a time series of observations for monitoring changes in geophysical parameters and fluxes, both of which are critical for modeling short term and long term climate change effects on our environment.

Except for a few cases, remote sensing data by itself cannot be used for computing fluxes. Exceptions include the geostationary satellites like GOES used for determining basin scale incoming solar radiation (Pinker and Laszlo 1990) and the newly employed NEXRAD systems for measuring precipitation and mesoscale wind fields (Klazura and Imy 1993). More often the remotely sensed data are combined with ancillary information, for example meteorological data from a nearby weather station. Within this framework, the water and energy fluxes are derived by using remotely sensed parameters of such relevant quantities as soil moisture, vegetation cover/land use, surface temperature, snow cover and surface albedo. Except for soil moisture, these geophysical quantities can be determined directly from optical (visible to thermal-infrared wavelengths) remote sensing data (Asrar 1989). For soil moisture, measurements in the microwave wavelengths show a strong sensitivity to water content in the upper few centimeters of the soil surface (Engman 1991).

A review of models for determining the surface energy balance is given by Jackson (1985), Carlson (1986) and Schmugge and Becker (1991). In general, the models can be divided into empirical-statistical and deterministic approaches (Schmugge and Becker 1991). The statistical approaches use ground-based meteorological measurements combined with remotely sensed data and correlate these observations with measured and modeled surface fluxes. The deterministic approaches vary in

complexity and involve numerical or analytical parameterizations relating the remotely sensed quantities and meteorological conditions to the components of the surface energy balance.

Even though remote sensing must be combined with modeling to compute large-scale fluxes of interest, the linkage of measurement technologies across spatial scales is not well understood. Estimates of the surface fluxes with remote sensing models have been verified at local scales (100 x 100 meters) using micrometeorological data (Moran and Jackson 1991) and at regional scales (10 x 10 km) using atmospheric boundary layer data (Sugita and Brutsaert 1990). Yet problems arise when attempts are made in estimating regional fluxes under nonuniform surface conditions (Brutsaert and Sugita 1992). Preliminary attempts at scaling remotely sensed data used to represent land characteristics and to compute fluxes indicate that the remotely sensed data and fluxes scale linearly (Wood and Lakshmi 1993). This, however, ignores the nonlinearity of surface-atmosphere interactions and the feedback between them (Jacobs and de Bruin 1992). Clearly, coupling the land surface and atmosphere from micro (10^1 meters) to meso (10^1 to 10^2 kilometers) scales is necessary before one can compute reliable fluxes over complicated landscapes. Atmospheric modelers are addressing this problem (e.g., Avissar 1992), but verification is difficult.

There are a number of surface parameters which are important for modeling the energy balance. As described previously, one such parameter is soil-water content. It can potentially be measured remotely by either passive or active microwave techniques. Microwave observations are not as susceptible to atmospheric effects, especially at wavelengths greater than 5 cm. In addition, these sensors can observe the surface through clouds, which is not possible with optical sensors. However, at present the satellite-based sensors are only able to quantify soil moisture in areas with sparse canopy cover (Owe et al. 1992). Passive microwave sensors at wavelengths that allow the observation of near-surface soil moisture under a wide range of canopy cover conditions would have too large a footprint for basin scale measurements (Jackson 1993). Active microwave does not have poor resolution, but is much more sensitive to vegetation and soil roughness effects as well as topography, making it difficult to extract soil moisture (Engman 1991).

Surface temperature is probably the variable most directly affected by the surface energy balance. Hence virtually all energy balance models have surface temperature as a main boundary condition. However, surface temperature is affected by both atmospheric and surface conditions. Atmospheric conditions provide what is probably the biggest problem faced in using remote sensing data. On site measurements of atmospheric properties with radiative transfer models have given accurate corrections, but this will not be practical for operational purposes. Other quasi-operational techniques have been developed, but need further testing with field data. In fact validation of atmospheric correction algorithms is rather scarce (Moran and Jackson 1991) and should be given a high priority.

Surface conditions include surface roughness, vegetation cover, surface and subsurface soil moisture. Studies document that from vegetation index-surface temperature relationships obtained with image data, surface moisture status, surface resistance and evapotranspiration limits can be determined (Carlson et al. 1990, Price 1990, Nemani et al. 1993). However, this relationship is unique for the surface and meteorological condition existing at the time of the observation, and thus cannot be applied to another climatic situation or surface.

Larger-Scale Heterogeneities with Emphasis on Topography

The interactions between the land and the atmosphere are made more complex as land surface features become more heterogeneous. This complexity affects both model application and measurement (eg., remote sensing) technologies Heterogeneities include land use (intensive cropping vs. native vegetation vs. forest vs. urbanization vs. water, etc.) and topography. While topographic effects are somewhat understood, research is needed to more thoroughly document these effects, and to transfer and modify knowledge of land-atmosphere interactions in fairly flat terrain to hilly and mountainous regions.

Within the ARS most investigations of topographic influence on atmospheric variables have taken place in conjunction with hydrologic studies at mountainous watersheds. These can be broadly grouped into arrows 1 and 2 (Fig. 1). Precipitation (liquid and solid) and air temperature have been the most common variables studied (Rawls and Jackson 1979, Hanson et al. 1980, Boyer 1984, Osborn 1984, Cooley 1988, Johnson and Hanson 1993), but wind, humidity, evapotranspiration (ET) and resultant soil conditions (moisture, temperature, frost depth) also have been analyzed (Feldhake and Boyer 1985, Hanson 1989).

Due in large measure to the hydrologic emphasis within ARS, precipitation is probably the variable which has been scrutinized most thoroughly. Significant knowledge gaps remain, however, concerning the effect of topography on atmospheric variability (including, but not restricted to, precipitation).

Recent studies have shown that simple precipitation-elevation relationships are insufficient to describe variability over even short distances (Garen et al. 1993), and that the concept of orographic scale must be considered to properly estimate precipitation (Daly and Neilson 1992). ARS watershed data from mountainous regions provide an unparalleled resource for investigating these concepts, especially at the watershed scale (approx. 100 to 500 km^2). Utilization of geographic information systems (GIS) now makes such investigations much more straightforward. Other related issues to be resolved include how the elevation dependence of precipitation changes both in time and space, and the influence of other topographic factors on precipitation (aspect, slope, distance from a ridgeline, moisture barriers and sources, etc.). All of these are of critical importance for estimating mean areal precipitation, which is a key input variable for most hydrologic models.

Characterization and modeling of wind, temperature, and atmospheric moisture variability is important both because they affect precipitation and because they have important, independent effects on large-scale hydrology. For instance, wind, and, thus, wind erosion are functions of topography because of the positive correlation of wind speed with elevation and exposure (usually). But wind erosion is also a function of vegetation cover and soil moisture, which are both interrelated to other factors (temperature, aspect, slope, elevation, precipitation, snow distribution, etc.). Thus, more work is needed in collecting and analyzing sufficiently dense (in space and time) meteorological data in topographically diverse areas. ARS watersheds are areas of great opportunity for such studies. In some cases, greater instrumentation is needed. In other cases, only data Q/C and analysis are required. These databases can then serve as validation sets for small scale atmospheric models.

It is clear from the discussions in the preceding sections of this paper that accurate and dense (both spatial and temporal) ground measurements are needed to validate models and calibrate remotely sensed estimates. The issue of scale is again central in these discussions.

Land surface heterogeneities are also known to be important for correctly parameterizing atmospheric models. Their degree of influence is dependent on both the variable in question and its scale (Avissar and Pielke 1989). Recently, the idea of representative elementary scale (REA) has been introduced, which is defined to be "...the critical scale at which implicit continuum assumptions can be used without explicit knowledge of the actual patterns of topographic, soil, or rainfall fields" (Wood and Lakshmi 1993). These authors suggest that for the land processes they investigated (latent and sensible heat fluxes, hydrologic runoff and the normalized difference vegetation index, or NDVI) this appears to be about 1000-1500 m. A shortcoming of these studies and other, intensive land-atmosphere field experiments is that they have primarily been conducted over relatively flat terrain. The ARS has a wide window of opportunity for investigating the variability of water and energy fluxes over complex terrain at their mountainous watershed sites. Efforts toward this end have already been expended, such as Monsoon '90 (Kustas et al. 1991), which combined remotely sensed data with ground measurements. Intensive, unified research campaigns are needed in other climatic regions and seasons, and in areas of even greater topographic diversity. The ARS must also form research alliances with atmospheric modelers (at all scales), which should produce improved models through improved parameterizations and ground measurements for validation.

Scientific Challenges

- Develop alternative verifiable modeling techniques that are based on known physical processes.

- Use remote sensing and atmospheric data to improve estimates of large-scale water and energy fluxes.

- Apply measurement and modeling approach to heterogeneous landscapes that include different land use and/or topography.

Research Opportunities

- Investigate the use of inverse modeling procedures to determine "effective" large scale parameters. This could be accomplished with combined measurement and modeling activities.

- Develop means of describing or incorporating the effects of small-scale spatial variability into large-scale models. It is likely that many of the small-scale effects have little impact on large-scale processes. What is needed is a means of evaluating the small scale impacts at a large scale.

- Develop alternative modeling algorithms that use measurable variables. This would allow for greater utilization of developments in remote sensing. They would probably not be based on the currently used potential/resistance approach.

- Develop measurement technologies that apply to relatively large areas. Remote sensing of soil-water content and relief, for example.

- Adopt a hierarchical study approach, where progressively larger scale models are validated in terms of smaller-scale models. It may be possible to fully validate small-scale models which may then be used to test larger-scale models.

- Carry out intensive large and small-scale field measurement campaigns in conjunction with modeling efforts. In this way we could link both our known technologies and modeling approaches.

- Develop land surface characterization approaches that incorporate critical variability. These will probably use both statistical and deterministic approaches to surface feature heterogeneity.

- Develop appropriate techniques for integrating both atmospheric and remotely sensed data from local to regional scales.

- Develop and apply technology that accounts for atmospheric effects.

- Develop microwave technology for measurement of soil-water content.

- Develop methods for estimation of mean precipitation in mountainous regions.

- Establish links between wind, temperature and atmospheric moisture and precipitation variability in mountainous terrain.

- Determine relationships between topography ET, soil moisture, soil temperature and frost depth.

- Carry out intensive parameterization and measurement campaigns in mountainous terrain.

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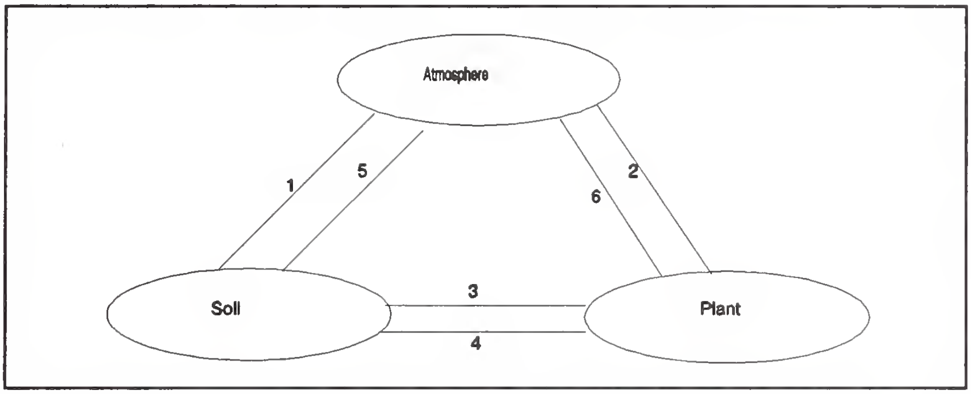

Figure 1. Interrelationships between atmospheric, soil and plant components of the terrestrial ecosystem.

Geohydrologic Opportunities in Agriculture and Watershed Research

J. A. Daniel[1], J. V. Bonta[2], G. N. Flerchinger[3], and D. B. Boyer[4]

Summary

The Agricultural Research Service (ARS) has made great strides in agriculture as a science. Large yields of high quality food have resulted in improved and healthier diets and longer life spans for Americans. However, public perception of agriculture is that current farm management practices may have inadvertently caused or contributed to environmental problems, especially water quality.

This paper provides discussion of general geohydrologic knowledge as applied to problem areas related to agriculture. The authors feel that gaps exist in certain areas of agricultural geohydrology and suggest that these gaps be addressed as part of the ARS's mission for the next century. The general categories to be addressed are environmental groundwater regulations and the role of agriculture, deep vadose zone research, applying new technology to groundwater research, technology transfer to enhance groundwater quality practices, and the role of watershed research.

Introduction

Geohydrology or groundwater hydrology may be defined as "the science of the occurrence, distribution, and movement of water below the surface of the earth" (Todd 1980). Todd includes the unsaturated or vadose zone, because with the interdependent boundary between the saturated and unsaturated zones and the bidirectional movement of water, no rigid distinction can be made between the two zones. Discounting precipitation, the quality and quantity of water that recharges the groundwater is a function of vadose zone thickness and lithology, fracture density, macropore density, degree of weathering, and geologic origin. However, the agricultural industry can also influence water quality and quantity that reaches the groundwater. Farming management practices have been shown to affect the environmental fate of agrichemicals (Gish and Sadeghi 1993). Such strategies include tillage, frequency and method of chemical application, cropping system, erosion control practices, and irrigation scheduling. The objective of this paper is to examine agricultural as well as geological factors that can influence groundwater, discuss gaps in current knowledge, and suggest possible directions for groundwater research as applied to agriculture.

[1] Geologist, USDA-ARS, P. O. Box 1430, Durant, OK 74702.
[2] Research Hydraulic Engineer, USDA-ARS, P. O. Box 478, Coshocton, OH 43812.
[3] Research Hydraulic Engineer, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[4] Hydrologist, USDA-ARS, P. O. Box 867, Beckley, WV 25802.

ARS Policies

Environmental issues are an ever growing concern. Increasing public awareness of the impairment of groundwater resources has caused careful scrutiny of industrial and agricultural activities to find primary causes of contamination. Agriculture is suspect to contributing to several environmental problems due to increased use of fertilizer and pesticides (Bulkley 1992).

ARS policies and priorities regarding research are defined in its 6-year plan for 1992-1998. The ARS goals are emphasized by the establishment of long-term, high-risk, fundamental, and applied research that fulfill its responsibilities. Public concern regarding agriculture is addressed by six objectives of the plan:

- Objective 1 - Soil, Water, and Air,
- Objective 2 - Plant Productivity,
- Objective 3 - Animal Productivity,
- Objective 4 - Commodity Conversion and Delivery,
- Objective 5 - Adequate Human Nutrition, and
- Objective 6 - Integration of Systems, using computer technology.

Groundwater research falls into Objective 1 (research on soil, water and air) and, to a lesser extent, Objective 6. Eight of the ten research areas identified in the plan for Objective 1 have a groundwater component. Relevant research areas address water quality, needs for fundamental knowledge, impacts on farming systems, chemical-application technologies, productivity, vulnerability of agricultural areas, evaluation methods, and conservation tillage. Also included is the agricultural impact on global change (GC) due to increasing carbon dioxide levels, and the impact of GC on agriculture.

Currently implemented research strategy includes the President's Initiative on Water Quality which addresses three primary needs:

- improved, inexpensive methods for sampling, measuring, and evaluating ground water quality,
- fundamental knowledge to provide the basis for improved management of chemicals used in agriculture, and
- improved agricultural chemical and production management systems.

Current Groundwater Research

Previous and current areas of ARS geohydrologic research can be categorized into the general topics of subsurface flow, groundwater recharge, contaminant transport, modeling, and global change.

Subsurface Flow

Several ARS locations are currently investigating groundwater and subsurface flow characteristics. These studies include development of solutions to regional flow in an aquifer and lateral subsurface flow (Columbia, MO), flow characteristics of karst terrain sinkholes (Beckley, WV), studies of groundwater response to snowmelt in mountain watersheds (Boise, ID), flow affected by subsurface layering within hillslopes (Coshocton, OH), and flow and contaminant transport in shallow fractured aquifers (University Park, PA).

A number of computer models simulate groundwater flow, the most popular being MODFLOW, the modular three-dimensional finite-difference model developed by the U.S Geological Survey (McDonald and Harbaugh 1988). Other models include: SUTRA (saturated-unsaturated transport), a finite-element simulation for saturated and unsaturated water flow (Voss 1984); TWODAN, a two-dimensional analytical groundwater flow model; FLONET, a two-dimensional steady-state vertical plane groundwater flow model; FLOWPATH, an integrated groundwater flow and pathline analysis system; and FLOWCAD, a two-dimensional transient horizontal plane groundwater flow package.

Groundwater Recharge

Groundwater recharge estimates are made by determining the portion of precipitation that passes through the root zone and reaches the aquifer. A knowledge of recharge rates and water supply is needed to assess potential groundwater contamination from agricultural sources. Geologically "sensitive" areas, areas in which water can percolate to the groundwater relatively quickly, are a major concern for agriculture relying on the use of agrichemicals. Geologically sensitive areas include glacial sand plains and outwash deposits, karst terrains, loess deposits, highly fractured rocks and fault zones - any geologic terrain susceptible to rapid recharge of surface water to groundwater.

Preferential flow is a mechanism which transports water and chemicals quicker than matrix flow through the vadose zone to the groundwater, whereby macropores play an important role in groundwater recharge. Because the water movement is rapid, the natural "cleansing" action of the soil is less effective and more chemicals can reach the aquifer. Several ARS locations are involved with modeling preferential and macropore flow (Riverside, CA; and Ft. Collins, CO), identifying flow paths and influence of macropores (Tifton, GA; Beltsville, MD; and University Park, PA), assessing the role of macroporosity in infiltration and chemical transport (Columbia, MO; Ames, IA; St.Paul, MN; Oxford, MS; West Lafayette, IN; Tucson, AZ; and Mandan, ND); and examining the influence of earthworms (Coshocton, OH; Urbana, IL; St. Paul, MN; and Kimberly, ID).

Several models have been developed to simulate preferential flow. The Root Zone Water Quality Model (DeCoursey and Rojas 1990) has a component for simulating preferential flow. Workman and Skaggs (1990) developed, PREFLO, a one-dimensional finite difference model using the Richards equation to simulate water flow through a soil profile. Jarvis et al. (1991) described a model using a non-steady-state transport of water and solute for macropores, while Grant et al. (1991) suggested using a simple stochastic model of infiltration.

Geophysical methods have been adapted for locating and characterizing the orientation of fracture fields (Urban and Pasquarell 1992). Contaminant transport of chemicals in fractured aquifers with regards to land use applications has received a great deal of attention in the Northeast (Gburek et al. 1991).

Contaminant Transport
Several ARS locations are involved with modeling water and solute transport processes (Riverside, CA, and University Park, PA), including two-dimensional modeling within the root zone (Beltsville, MD and Ft. Collins, CO), field scale transport (Ames, IA), and modeling the influence of flux relations and ridge-till operations on water and solute movement (St. Paul, MN). Researchers are involved with mapping underground concentrations of chemicals leaking from farm lagoons using electromagnetic techniques (Florence, SC), assessing affect of poultry litter applications as related to soil characteristics (Raleigh, NC; Durant OK), studying flux relations on movements of nitrates and herbicides (St. Paul, MN) and determining the movement of nitrates due to tillage (Durant, OK).

Commercially available computer models which deal with contaminant flow were developed by the environmental field and simulate the movement of contaminant plumes from leaking underground storage tanks (UST's) or chemical spills. Such models include: PULSE and CXPMPM, two models which simulate the fate of a previously distributed source introduced into the aquifer; and TDPLUME and TWODPLME, two-dimensional analytical solute transport models for confined and unconfined aquifers.

Considerable effort is being directed towards chemical transport particularly nonpoint-source pollution from increased use of fertilizer and pesticide and point-source pollution from feedlots, accidental spills, improperly cased wells, and fracture-flow in karst regions.

Non-point source pollution. Nonpoint-source groundwater pollution can occur in geologically sensitive regions where agrichemicals are heavily used. The common chemicals for non-point source groundwater pollution are nitrate, pesticides, and salinity.

Nitrate problems in groundwater typically occur in locations with heavy fertilization usage, such as the Corn Belt, and regions with sandy soil using irrigation and fertigation (Keeney 1986). Previous studies show that regional increases of nitrate in shallow groundwater have occurred concurrently with the increased non-point source use of chemical nitrogen fertilizer (Hallberg 1986b, Wall and Montgomery 1991, Adelman et al. 1985). Isotopically labelled fertilizer nitrogen shows similar results (Hallberg 1986b, Chichester and Smith 1978). Use of riparian zones has been shown to effectively remove nitrate and phosphorus from shallow groundwater and show a general improvement in groundwater quality (Lowrance and Leonard 1988, Cooper 1990, Ambus and Lowrance 1991, Haycock and Pinay 1993, Lowrance et al. 1985).

Pesticides usage has increased over the last 30 years to control weeds and pests which can lower crop production and current usage of pesticides is even higher with minimum tillage. More reports of pesticides in groundwater are being made, but this is probably a result of lower detection limits of analytical equipment. For example, 16 pesticides (mostly herbicides) were detected in groundwater aquifers in Iowa (Kross et al. 1992), but levels were well below the acceptable EPA limits. ARS scientists have found that leaching of alachlor, metolachlor, atrazine and other herbicides could be prevented when those herbicides were contained in release-controlled starch-encapsulated granules (Lafayette, IN). By encapsulating certain insecticides in cornstarch, it was found that the use of some insecticides in the corn belt could be cut by up to 98%.

Saline problems are commonly associated with irrigation, springs (or seeps) and low-lying depressions in the arid western United States where evaporation rates are high. Groundwater is used for irrigation in the arid southwest to maintain high crop yields, however, dissolved solids and chemicals in groundwater can be deposited as salts in a soil (Keeney 1989).

Point source pollution. Agricultural point-source pollution occurs in areas of intensive animal production (Keeney 1986). Groundwater research in the hydrologic unit area (HUA) projects has suggested that agricultural pollution of groundwater may often be caused by isolated management practices rather than broadscale management practices. Potential point-source pollution locations include cattle feedlots, poultry houses (turkeys, laying hens, and broilers) and swine operations - any operation that deals with handling manure. HUA research in a karst area revealed that much of the groundwater contamination was coming from sinkholes associated with concentrations of livestock (Pasquarell and Boyer 1991). Agricultural drainage wells in some parts of rural Minnesota are used to drain subsurface and surface water to groundwater. Such methods can transport nitrogen and pesticides to groundwater causing potential problems (Baker et al. 1985).

Sampling Methods and Analysis

Sampling of groundwater and soil water from the vadose zone can be a major problem because there is not an wholly acceptable method of obtaining a representative sample. Debate exists on the amount of purging necessary for an observation well to obtain a representative groundwater sample - one well-volume or more, or even if purging if necessary. One approach developed by ARS scientists at University Park, PA, is to measure chemical changes in the well water during purging until chemical concentrations stabilize. After stabilization occurs, a sample can then be collected (Urban 1988, Pionke and Urban, 1987).

Samples of soil water from the unsaturated zone are generally obtained by vacuum lysimeters. These approaches have been developed primarily by the environmental industry for monitoring spill sites, sewage lagoons, and community landfills. Modification of vacuum lysimeters with stainless steel and teflon allow sampling of pesticides (Smith and Carsel 1986). A wick sampler (passive capillary sampler) has been developed to obtain a water sample without using a vacuum by drawing the sample from the soil or rock in the same way as the wick of a candle works (Knutson and Selker 1993).

Watershed Modeling

ARS has been successful in developing watershed models and decision aids for groundwater and water quality concerns. Several models, were mainly developed for surface water studies and are useful tools for preliminary watershed research. However, incorporation of a groundwater recharge and/or groundwater flow component is necessary. These models include AGNPS (Young et al. 1987), EPIC (Williams et al. 1984) and CREAMS (Knisel 1980). GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) was developed from CREAMS and is an important tool for groundwater researchers and managers by estimating chemical loading to the groundwater (Leonard et al. 1987).

Databases. The ARS has operated over 600 watersheds at one time or another during the past 40 years (DeCoursey 1992). Three hundred thirty-three watersheds have a comprehensive data base available. Of these 333, 140 are currently active. Two hundred-nineteen watersheds have records longer than 10 years, and 48 have records longer than 30 years. Available information includes soil information, land use, break-point rainfall, runoff, sediment yield, meteorological information, soil moisture, infiltration rates, and nutrient and pesticide concentrations (DeCoursey 1992). Groundwater level data are available for some of the watersheds but not all.

Currently, data are being collected and databases maintained on several large ARS watershed. These watersheds include the Herrings Marsh Run (North Carolina), Reynolds Creek (Idaho), Walnut Gulch (Arizona), Southern Piedmont (Georgia), Treynor (Iowa), and Little Washita

(Oklahoma). A large amount of data is available, but continuing work is being done to convert information present as chart data form into computer files with a standardized format.

A pesticide properties database was developed with SCS and CES scientists (Wauchope et al. 1992). The database has been incorporated into computer simulation models and used as the basis for pesticide risk screening tools.

Geographic information systems. Geographic information systems (GIS) are designed for the processing, retrieval and display of spatially referenced data. Groundwater risk assessment from contamination is a logical application of GIS using information, such as well location, soil type, depth to groundwater, aquifer size, and hydraulic conductivity (Evans 1987). DRASTIC is a model which creates a standardized system to evaluate potential groundwater pollution (Aller et al. 1987).

Problems with parameter estimation due to the lack of data can result in shortcomings for using GIS. Sources to obtain parameters include established databases of groundwater depth, precipitation, soil moisture and soil type. When established databases are not available though, remotely sensed (e.g. Landsat imagery) may be useful at estimating the needed parameters. In areas where data exist but are sparse, kriging and other spatial variability techniques can be useful (Tarboton et al. 1993).

Global Change

It is theorized that if a doubling of CO_2 content in the global atmosphere occurs, a 2-6°C increase in the average global surface temperature and an approximate 10% increase in mean global precipitation would occur by the middle of next century (Knox 1990, Hegeveld 1987, Waggoner 1989). However, increased precipitation does not imply a uniform distribution around the world. Some regions will become drier while other regions become wetter. Not only can total rainfall change in amount in a given area, but rain events may change intensity and become more erratic (Gall et al. 1992).

Agricultural regions receiving less rainfall would increasingly rely on irrigation to meet production demands. Saline seeps, a problem in the western United States, may result from intensive irrigation. Less precipitation would also indicate less groundwater recharge and increase demand on groundwater resources. Agriculture is the main user of fresh water on the planet, but with demands for freshwater increasing from urban areas and non-agricultural industry, conflicts over groundwater use are forthcoming (Gall et al. 1992).

Regions receiving increased annual precipitation will probably experience increased chemical and nutrient leaching to groundwater and increased surface removal of applied chemicals. This presents a greater potential for contamination of groundwater by pesticides and fertilizers (Gall et al. 1992).

Scientific Challenges

ARS and other agricultural agencies have compiled a great deal of information critical to obtaining maximum crop yields from the land. This research has emphasized maximum yield and profit generally at the expense of land and water quality. As more information becomes available from agricultural research, research emphasis and needs can change in order to achieve the goals required by the ARS. Listed below are the primary areas of concern for geohydrologic research as related to agriculture.

The Role of Agriculture and Environmental Regulations

The United States has 50 percent of its water supplied by groundwater resources and rural areas use 90 to 95% of that groundwater (Stewart 1987). Agricultural livelihood is dependent on adequate supplies of potable groundwater. It is in agriculture's best self-interest to protect groundwater resources from contamination, so potable groundwater supplies can be maintained.

Agriculture has received negative publicity because of its role as a non-point source polluter due to increased use of agrichemicals and as a point-source polluter from confined animal production. Consequently, with this negative perception, agriculture is susceptible to environmental regulations in an effort to reduce pollution from agricultural sources and improve water quality. For example, river basin commissions and state regulatory agencies will probably impose controls of nutrient loss for all aspects of agriculture. This will result in the financial punishment of agriculture during a time when farm profitability is marginal.

Deep Vadose Zone

The root zone has been the main emphasis of agricultural sciences. Soil moisture and agrichemicals which have passed through the root zone are considered out of the agricultural system and largely ignored. The deep vadose zone, the unsaturated zone lying between the bottom of the root zone and the top of the water table, varies in thickness across the country - it may be hundreds of feet thick in one region while in other areas, it may not exist. Little or no information is available about degradation of pesticides and chemicals, denitrification, impact of macropores at depth, mechanisms of nutrient movement, rates of chemical and nutrient movement, spatial and temporal variability of the capillary fringe, and capillary fringe chemistry. This type of information is critical because it is easier and cheaper to contain and control pollutant movement in the vadose zone than after it reaches the water table.

Technology Transfer

Several agricultural management practices have proven advantageous to enhancing surface and subsurface water quality. For example, management practices which have proven effective so far in controlling nutrient movement in groundwater include:

- nutrient management systems to reduce application of nitrogen to cropped fields and subsequently decrease nitrate concentration in groundwater and nitrogen loading in groundwater discharged from the site (Hall and Riser 1992, Hall 1992, Diesel et al. 1993);

- use degree-day concept to determine when nitrogen is available from the breakdown of buried plant residues (Honeycutt et al. 1991) and reduce nitrogen fertilizer applications;

- controlled-released fertilizer (Alva 1992);

- nitrification inhibitor (Peterson and Frye 1989);

- denitrification (Korom 1992); and

- farmponds and riparian zones.

Technology Advances

Previous geohydrologic research relied on drill hole cuttings, cores, and borehole geophysics to obtain information about lithology, sediment size and distribution, and hydrologic characteristics,

such as hydraulic conductivity. Such methods are labor intensive and expensive. New methods to study the saturated and unsaturated zones have been developed or refined, which can provide opportunities to resolve, in greater detail, spatial properties of the soil and subsoil. Indirect sensing methods originally developed for the mining and petroleum industries have used computer techniques and equipment refinement to increase resolution in which to characterize, monitor and assist in the large-scale quantification of vadose zone water movement and shallow groundwater movement. These techniques include ground penetrating radar, borehole geophysics, shallow seismic, and electrical resistivity methods. Information provided by geophysics can result in 3-dimensional models describing spatial variability of fractures and water movement.

Drilling technology has advanced with the development of horizontal and steered-direction drilling rigs. Previously, only petroleum companies could afford this type of equipment, but the cost has decreased and this technology is now available for environmental and agricultural research. This equipment will provide access to groundwater sampling sites and allow measurement of hydraulic head that was not previously available.

New drilling techniques and methods of well development can locate and provide access to groundwater resources in karst and fractured-bedrock regions that previously were inaccessible. Because of variably-spaced fractures, groundwater supplies were not dependable and difficult to locate. Finding reliable groundwater sources could enhance the agriculture and economic environment of a region.

New tracers that are safer and more accurately mimic the transport of pollutants should be developed and used for defining preferential flow paths, particularly in karst and geologically sensitive areas.

Watershed Basins

Early watershed development and research was based primarily on surface runoff. This is understandable since a scientist can see drainage patterns, monitor the runoff and flow after a rain event, and analyze the runoff for nutrient and sediment. Groundwater research is becoming a major part of watershed research. But, topics that should be addressed for researching groundwater in a watershed include more accurate definition of groundwater boundaries, impact of landscape sensitivity on groundwater, impact of shallow groundwater on deeper groundwater, and the interrelationship between groundwater and surface water.

Groundwater boundaries. Groundwater does not necessarily follow the same watershed boundaries as does surface water. To better understand the impact of groundwater in a watershed and its contribution to the hydrologic budget, "closed" or isolated groundwater watersheds need to be established. Two methods to achieve this goal include establishing watersheds where surface water and shallow groundwater share the same watershed boundary or more accurately define the groundwater flow into a watershed. Some existing watersheds - Urban's Knob (OH), Big Spring Basin (IA), WE-38 (PA), and Reynolds Creek (ID) - do have the same watershed boundary for both surface and shallow groundwater. A "closed" watershed is an ideal situation for accurate determination of the role of precipitation and nonpoint-source pollution to groundwater quality. Existing watersheds that are not closed need better delineation of the watershed boundaries to more adequately describe the overall groundwater picture. This is remedied by installation and monitoring of groundwater wells. However; a common problem in this situation is cost - groundwater well installation is expensive. Installation of a groundwater network to monitor groundwater contribution and flow within a watershed could deplete the unit's budget.

Impact of landscape sensitivity on groundwater. Various landscapes in a large watershed may be similar in surface appearance, but they may represent different geologic depositional environments, undergone different tectonic processes, or achieved various levels of weathering. Varying geologic conditions can complicate the attempts to use strictly surface land use and surface measurements to categorize recharge area sensitivity to agriculture inputs. Groundwater recharge rates, in geologically sensitive areas, are controlled by a number of parameters, including variability of fracture density and depth, aquifer lithology, degree of subsurface limestone cavern development, weathering of impervious strata, gypsum and other soluble evaporitic sedimentary rocks, depth of aquifer "bottom" and layered aquifer systems. Geologically sensitive areas include karst limestone, glacial sand plains and outwash deposits, loess deposits, strata with water-soluble minerals, and fault zones.

Impact of shallow groundwater on deeper groundwater. Sensitive landscape areas have been shown to affect only shallow groundwater, but it may be a function of time before deeper aquifers are also affected (Hallberg 1986a). While data do not exist showing the movement of agrichemicals to deeper aquifers, documentation does exist concerning complex cleanup of environmental sites where chemicals have moved through fractured bedrock to deeper aquifers. The deeper aquifers are generally used for community water supplies. The primary question would be if the movement of agrichemicals to deeper aquifers is a serious threat.

Interrelationships between groundwater and surface water. Methods to estimate groundwater flux (or base flow) into a stream channel have been established, but this research is principally for a water or chemical balance for the a watershed. The groundwater/stream water interface (hyporheic zone) has been largely ignored. Microbiologists, using aquatic macrophytes, are able to determine the presence of groundwater as it enters a stream bed (hyporheic zone) and gauge subsurface water direction (White 1993, Palmer 1993, White et al 1992). Based on this research, the base flow is not uniform in its relation to the stream channel but is variable. Also, the chemical component of the ground water is critical for the survival of the aquatic life. Contaminants carried in the groundwater and introduced to the stream as base flow can severely impair water quality and affect aquatic life forms. Likewise, Tremolieres et al. (1993) have shown that pollutants can be unintentionally introduced to the groundwater via the stream. For a research watershed, spatial variability studies of the hyporheic zones of stream channel should be incorporated into watershed studies to accurately measure groundwater fluxes into a fluvial system and identify point-source locations of groundwater pollutants into a fluvial system.

Research Opportunities

Research opportunities for the next century that are most critical for geohydrologic research are: the role of agriculture and environmental regulations; the role of the deep vadose zone on groundwater quality and quantity; the impact of technological advances with groundwater research; and future roles of watershed research.

1. Environmental impacts from agriculture must be examined, placed in perspective, and understood by policy makers and the general public, so environmental policy decisions can be made from reasonable and accurate information. Suggestions to accomplish this goal include:

   - development of methodology to calculate surface and subsurface nutrient movement and water budgets within regulatory frameworks;

- providing accurate predictions of various landuse and treatments on surface and subsurface hydrology and water quality.

2. The realm of the agricultural science must include the soil and subsoil below the root zone since this can indirectly affect crop and animal production and directly influence environmental quality. Opportunities for deep vadose zone research include:

    - quantification of the physical properties of consolidated and unconsolidated material within the vadose zone that influence the movement of water as unsaturated matrix water and variably saturated and unsaturated fracture water; and

    - documentation is needed to describe deep leaching processes and aquifers that are controlled by rock fracturing and fracture-enhanced solution weathering. Two major unknowns exist in aquifer characterizations: storativity and flow velocity distributions.

    - determination of the geochemical and kinetic processes occurring in the deep vadose zone and their impact on groundwater quality. These processes include degradation of agrichemicals, denitrification, and mineral surface chemistry and adsorption-desorption properties of minerals, under conditions of constant temperature, moisture, and redox conditions but varying chemical quality and quantity of the percolate flux. Principal minerals to examine include manganese, iron and silica hydrous oxides.

3. Technical and electronic advances should be incorporated in ARS subsurface data collection. Opportunities exist in:

    - use of new technology to research water development enhancement in fractured rock in regions where groundwater supplies were previously unreliable;

    - examination and measurement of fractured rock porosity and its distribution using enhanced geophysical techniques and 3-D modeling;

    - use new techniques, such as directional drilling to aid in the measurement of hydraulic head and in-situ chemical sampling in karst and fractured-bedrock regions; and

    - utilize a wide variety of new tracers to determine ground water velocity to aid in defining preferential flow paths in karst regions.

4. More attention and exposure must be given to agricultural management practices as a cost-effective environmental maintenance strategy. Research includes:

    - quantification of agricultural management practices for use as effective environmental enhancement procedures; and

    - development of parametric and/or stochastic models that enable the inputs from complex agricultural and water inputs to interface with other environmental resource agencies (and possibly environmental regulatory agencies) which operate at different dimensional scales than do current agricultural farming units.

5. Use of the research watershed is the most effective and comprehensive approach to determine the role of agriculture on groundwater quality, impact of global change on agriculture, and determining the effectiveness of management practices in agriculture. Needs to be addressed by future watershed research include:

   - other methods incorporating geobased modeling and upland stream low-flow analyses may detect subtle changes in watershed recharge aquifer yield not evident strictly from land use patterns.

   - combinations of geologic, geophysical and more traditional hydrologic investigations are required to quantify agricultural nutrient transport pathways in sensitive regions.

   - incorporation of 3-dimensional maps of geologically sensitive regions into landscape analyses may help resolve past hydrologic problems.

   - determine landscape sensitivity to surface activity and its resulting impact upon subsurface waters.

   - quantify aquifer water resource response to changes in percolation volume and water quality.

   - for a research watershed, spatial variability studies of the hyporheic zones of stream channel should be incorporated into watershed studies to accurately measure groundwater fluxes into a fluvial system and identify point-source locations of groundwater pollutants into a fluvial system.

   - monitor water quality of deeper aquifers for agrichemicals in agricultural watershed. This will involve deep percolation and interaction of shallow and deep aquifer studies on agricultural lands to determine extent of agrichemical and nutrient movement.

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Effective Use of USDA-ARS Experimental Watersheds

D.C. Goodrich[1], P.J. Starks[2], R.R. Schnabel[3], and D.D. Bosch[4]

Summary

The geographically distributed experimental watersheds operated by the USDA-Agricultural Research Service (ARS) constitute one the best networks of its kind in the world. The watersheds are, and continue to be a national treasure of hydrologic knowledge and history. However, changing demands and monetary constraints require a critical re-examination of the ARS Experimental Watershed Research Program mission to ensure effective utilization, maintenance and continued improvement of this precious resource. To set the stage for this endeavor, a historical perspective of ARS watershed establishment is presented. Critical gaps within the current watershed network are examined and significant research opportunities which build upon, and enhance the status and capabilities of the ARS Experimental Watersheds are discussed. Finally, crucial decisions must be made to define the appropriate role of ARS experimental watersheds and level of data collection within them to address new and emerging agricultural and societal needs under strict budgetary constraints.

Introduction

> *"The collection of basic data is an attribute of intelligent sovereignty; a wise sovereign seeks to know the value as well as the extent of its domain." (Langbein 1965)*

Langbein (1965) went on to define the concept of a network for collection of basic hydrologic data. "Its component parts must be related to one another, that is, each station, point, or region of observation must fill one or more definite niches in either space or time." While Langbien's focus was on national networks, Neff (1965) more thoroughly discussed the local network, which embodies the philosophy of network design for individual ARS experimental watersheds. In a local, intensive network more precise, quantitative data is collected for specific hydrologic interpretations. This is in contrast to a national, or extensive network which collects qualitative information for broad interpretation by providing regional "index" information. Significant scientific attention was given to the establishment of hydrologic networks and representative and experimental areas during the International Hydrologic Decade (Tison 1965a,b). By the time of these publications (Tison 1965a,b), the ARS and its predecessors already had a relatively long and impressive history of intensive, local network, hydrologic data collection.

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[1] Research Hydraulic Engineer, USDA-ARS 2000 East Allen Road, Tucson, AZ 85719.

[2] Soil Scientist, USDA-ARS, P. O. Box 1430, Durant, OK 74702.

[3] Soil Scientist, USDA-ARS, Curtain Road, University Park, PA 16802.

[4] Research Hydraulic Engineer, USDA-ARS, P. O. Box 946, Tifton, GA 31793.

The ARS Experimental Watershed Program grew out of early, depression era efforts by the Civil Conservation Corps (CCC) and the Soil Conservation Service (SCS). Kelly and Glymph (1965) provide a description of the early history of the watershed program as we know it today. They begin by describing early research associated with the 1930's conservation motto of "stop the water where it falls." The research focused on the merits of upstream watershed conservation to hold the water and to reduce runoff and erosion. This research was geared to studying on-site problems and concentrated on field-sized watersheds up to roughly 10 hectares and, to a large extent, utilized paired watershed analyses. In 1935, major research stations were established in Coshocton, OH, Hasting, NE, and Riesel, TX to examine fields and watersheds up to several hundred hectares (square kilometers) in size. Research still concentrated on on-site effects of tillage and management practices, but plot and lysimeter studies were incorporated. Kelly and Glymph (1965) describe the research during this period as largely empirical with emphasis on accurate data collection. In the 1950's, emphasis moved to a larger scale, and national programs were developed for controlling flood waters and sediment, as well as assessing downstream effects on watersheds up to 1,000 km^2. Many of the experimental watersheds were transferred to the newly formed USDA-ARS in 1954.

There was early recognition of the scaling problems in transferring knowledge from data collected at the small scale to larger watersheds (Harrold and Stephens 1965). This problem and growing concern of downstream, off-site impacts of upstream watershed practices resulted in the establishment of a subset of larger ARS experimental watersheds associated with new watershed research centers in a number of hydroclimatic regions in compliance with U.S. Senate Document 59 (Great Plains, Northeast, Northwest, Southeast, and Southwest Watershed Research Centers in Chickasha, OK; State College, PA; Boise, ID; Tifton, GA; and Tucson, AZ; respectively). The goal of the watershed research centers was to select a representative basin and establish satellite basins, that were less well instrumented, to extend the data and findings from the primary watershed center. Nested watersheds and unit source areas on major soil types were included in the watershed designs to investigate scale effects.

A recent overview of ARS experimental watershed research is given in DeCoursey (1992). A description of data acquisition programs and an assessment of the quality of collected data at many of the experimental watersheds is also described in Johnson et al. (1982). Based on data from the Hydrology Laboratory in Beltsville, Maryland, as of January 1, 1991, ARS has operated over 600 watersheds in its history. Of the 600 watersheds, a comprehensive database is available from the Hydrology Laboratory for 333 of these watersheds. Currently, 140 watersheds are active and collecting a variety of data. Table 1, reproduced from DeCoursey (1992), describes the size distribution, length of record and primary land use of the active watersheds. The geographic location of both active and closed watersheds is illustrated in Figure 1 (as of January 1, 1992). In many of the locations depicted on this figure, multiple watersheds exist or have existed. In general, active watersheds are still well distributed over the contiguous 48 United States.

Early experimental watershed research needs were largely oriented to solving pressing field problems. In 1965, Hickok and Ree (1965) stated that the objectives of ARS and its predecessors were: "...1) accumulation of basic-rainfall-runoff data, primarily for design of soil and water conservation structures; 2) study of the effects of land-use and treatment practices on the runoff and sediment production from upstream watershed source areas; and 3) evaluation of overall effects of watershed management and protection programs on flood expectancies, and net water and sediment yield of larger, complex watersheds." Additional objectives were also more formally defined by annual SCS research needs statements (Kelly and Glymph 1965). Since then, these research objectives have changed and evolved to address current problems such as chemical water quality and

climate change in addition to improving our understanding of basic hydrology and soil-water-plant relationships.

In a 1991 report, the National Research Council (1991) noted that water resource applications have often preceded science. For example, those in applied professions such as Civil and Agricultural Engineering are credited as being largely responsible for water-related health and safety enjoyed by modern society. In a parallel vein, the establishment of ARS experimental watersheds was largely justified on grounds of on- and off-site impacts related to management and human applications. This does not imply that improved scientific understanding was not a goal of early ARS experimental watershed research (Holtan and Whelan 1965, Harrold and Stephens 1965, Kelly and Glymph 1965, Holtan 1970), but that establishment and watershed funding was primarily driven by water resource applications and associated impacts. However, with current concerns of potential global change impacts, a realization has come forth for an improved, multidisciplinary understanding of the coupled water, energy and biogeochemical cycle over a wide range of temporal and spatial scales. The National Research Council (1991) concluded that to meet this challenge, a more scientific, less applications oriented approach must be utilized. The critical role of experimental watershed data in this quest for scientific understanding was reiterated as they stated, "The needed understanding will be built from coordinated, long-term data sets (both at fine and large spatial scales) and founded on an educational base in the geosciences." (National Research Council 1991). The scientific strength of ARS and its Experimental Watershed Program place it in a strategic position to take up this challenge.

Scientific Challenges

The ARS experimental watersheds must play an integral role in meeting the challenge of addressing societal needs for agricultural production and environmental protection under non-stationary global climatic conditions. Complex computer models have been, and are being developed, to address these needs. However, confidence in computer models and their simulations can only be acquired via verification with observations. It must be recognized that in many cases the complexity of computer models far exceeds our ability to economically collect data to parameterize and verify these models. To meet this challenge, a variety of critical gaps which exist in the ARS experimental watershed data collection and associated database organization must be addressed. In the current budgetary climate, this will force re-examination and prioritization of watershed objectives as well as necessitate closer interagency cooperation. We must reevaluate how the long term records are being used and ask ourselves several critical questions. Are we collecting the correct information, or are we collecting data for data's sake? Are we collecting data that does not aid or help us address our research objectives? Are we operating at the proper spatial and temporal scales? Are there additional types of data that we need to collect?

Critical Measurement or Information Gaps

Due to changing research needs and objectives, auxiliary measurements, not envisioned by those who established the experimental watersheds, are required. A list of critical measurements and/or information gaps that exists at many, and in some cases, all of the ARS experimental watersheds is contained in Table 2. Local conditions would of course modify needs and methods for each of the items contained in this table.

To better understand land-atmosphere interactions and the water balance itself, it is essential that we monitor the energy balance. It is no longer sufficient to treat evapotranspiration as a residual in the water balance. Longer term water quality and primary nutrient records are required at the

watershed scale to both establish trends and study management effects. Because the transport dynamics and residence times of streams and lakes are vastly different than field-scale dynamics, temporal records of greater length are required to track contaminants once they are transported out of the field. In addition to longer duration, the temporal sampling of water quality measurements must be frequent enough to characterize individual storm effects. The spatial sampling scale must also be small enough to evaluate causal relationships. The suite of measurements taken by the USGS National Water Quality Assessment Program could provide a model for the ARS experimental watershed program to initially evaluate.

To organize spatially distributed experimental watershed data and characteristics it is essential to develop high quality GIS coverage layers for the basin characteristics listed in Table 2. This need will become more evident in the application and testing of more complex, multi-dimensional large area hydrology models (Arnold et al. 1994). To further large area hydrologic applications it is essential to acquire remotely sensed data over the experimental watersheds. Due to both the data collection density and length of record it is likely that ARS experimental watersheds will be excellent locations to test methodologies and model strategies which directly utilize remotely sensed data. To more fully understand the long term implications of climate change, the ability to model feedback mechanisms between the biosphere, atmosphere and hydrosphere must be developed. This necessitates ecological and biomass characterization on ARS experimental watersheds. Similarly, to better understand and model nutrient cycling and water quality, biogeochemical balance measurements must be conducted. To a large degree, the ability to implement complex hydrologic models has exceeded the ability to verify these models with current measurements. Spatially distributed models must be verified with distributed observations, nested within the catchments being modelled. Without collecting this data it is not possible to draw conclusions regarding the within-catchment behavior of a models. These measurements will also be needed to go beyond one-dimensional modeling. To realistically identify possible long term climatic trends in a highly variable hydrometeorologic environment we must attempt to extend experimental watershed records back beyond the modern day record. Finally, to properly interpret both our historical database and future measurements, auxiliary, or metadata, information about the measurements must be compiled. Metadata, or "data about data", describing instrumentation, estimates of uncertainty and conditions which affect our measurements such as basin land use and management practices is essential for inter-watershed comparison and historical data interpretation. Computer compilation of historical metadata will become even more important as the scientists who established ARS Experimental Watersheds retire.

Limitations

At many ARS watersheds, an excellent job is done collecting some of the measurements listed in Table 2. From a budgetary standpoint, any one watershed location may not be able to collect all the information contained in the table. Budgetary considerations for instrumentation are one obvious limitation. An additional consideration that cannot be ignored is the necessity for trained personnel to make the measurements and interpret the data. Expertise to make many of the measurements listed in Table 2 is not widely available among the ARS experimental watershed/hydrology personnel. However, to tackle some of the national research problems related to water quality and global change facing the ARS, additional measurements will be required. If all the measurements at all the watersheds cannot be made, a subset of watersheds must be identified with a prioritized list of those measurements that will enable interregional watershed comparisons and continental assessments.

A second limitation is the size of the ARS experimental watersheds. It is very unlikely that current watersheds will be expanded with a level of instrumentation density that currently exists. This will limit the possibility of scaling up to and coupling with mesoscale meteorologic models and beyond to global climate models (GCM). ARS cannot realistically instrument and analyze all watershed scales and the proper scale(s) which would best meet present and future ARS objectives must be determined. Where does the scope of ARS inquiry begin and end? This must be resolved and should be closely tied to ARS objectives. To conduct large area analysis beyond ARS watershed scales will require utilization of data collected by other agencies such as National Weather Service (NEXRAD radar-rainfall estimates), USGS, NASA, and others. In turn, many of these agencies have, and will, look to ARS for high quality ground truth data and support measurements.

Deficiencies in our Underlying Scientific Knowledge

The problems associated with hydrologic spatial heterogeneity and cost efficient methodologies to measure it over large areas will continue to challenge the ARS Experimental Watershed Program (Bosch et al. 1994). Simple, cost effective instrumentation and methods to measure a variety of variables (i.e. soil hydraulic properties, soil moisture, erosion, deposition and sediment transport rates, water quality, hillslope distributions of overland flow velocity and depth, expanding and contracting areas of saturation, contributions to and from groundwater, etc) are still elusive for many of the variables mentioned.

For many measurements the principle of uncertainty will compromise measurement of other important watershed response variables. For example, from a geomorphic perspective, building a runoff measuring structure does not allow natural channel degradation, disrupts the gradeline and severely interferes with sediment transport. Due to measurement difficulty, some of the most significant watershed knowledge deficiencies arise in the subsurface environment. Knowledge of processes below the root zone and above the water table; surface water-groundwater interactions; travel time through the subsurface environment; and of simple methods for aquifer characterization, wetlands delineation and subsurface stratigraphy are scant in comparison to knowledge of surface processes.

The importance of an experimental watershed program like the one operated by ARS is underscored by the fact that other agencies are initiating similar programs. The U.S. Geological Survey has initiated a similar program, although on a much smaller scale with a slightly different focus. The Water, Energy, and Biogeochemical Balance (WEBB) program has begun establishing a number of small research watershed sites over a range of hydroclimatic zones (Kelmelis 1993). Additionally, the National Science Foundation Long Term Ecological Research (LTER) program (National Research Council 1991) also has sites in a variety of hydroclimatic regions with focus on interdisciplinary ecological research. ARS, with its established watersheds and long hydrologic records, is well positioned to provide more immediate answers to pressing issues than are newly established programs. However, to be successful ARS must avail itself to the opportunities to retrofit watersheds to obtain additional critical data.

Information Base

One class of experimental watershed database exists at individual ARS watershed locations and another at the ARS Water Data Center at the Beltsville Hydrology Laboratory. In addition to the long term rainfall-runoff data collected and forwarded to the Water Data Center, the individual locations often have additional extensive data sets. These include short-term, project oriented special collections, water quality and sediment data, GIS and remotely sensed data and historical

descriptive information (metadata). Much of this data is not in computer compatible format and is in danger of being lost.

The combined ARS database formed by linkage of the individual experimental watersheds through central data deposition and organization by the ARS Water Data Center truly constitutes a "national network" of intensive watersheds in the spirit of Langbein's (1965) discussion. Efforts must be made to submit and pull in the additional data sets at the individual experimental watersheds. For the special MONSOON '90 multi-disciplinary field campaign (Kustas et al. 1991) on the Walnut Gulch Experimental Watershed, a special project data set is being assembled at the Water Data Center. To accomplish this for ongoing projects and to pull in the types of data listed above that are not normally submitted, the Water Data Center will require extra resources.

Another critical issue that the ARS must face is quality control for experimental watershed data. A U.S. Dept. of Agriculture (Johnson et al. 1982) report documents results of a survey to identify the key instrumentation and data quality concerns of the ARS research program. Reports of the survey were obtained from each data collection center but no formal recommendations or uniform quality control guidelines were established. In the opinion of Dr. Ken Renard (personal communication 1993), overall agency quality control of experimental data is virtually non-existent. It is assumed that each watershed established its data collection and instrumentation program based on guidelines in Agricultural Handbook 224 (Brakensiek et al. 1979). However, this reference is not all inclusive and adaptations have had to be made to local conditions.

Dr. Kenneth G. Renard (personal communication 1993) also noted several trends that may adversely affect the ARS Experimental Watershed program. First, there are very few persons hired who are truly instrumentation oriented experimentalists. Second, many locations have not been stressing data collection and processing experience for new hires as they have in the past. The current system of evaluation of ARS scientists may have contributed to this trend. In contrast, in the late 1950's and 1960's L.M. Glymph insisted every ARS scientist involved in the hydrology program would be involved in instrumentation and data collection. Most of the hydrology researchers of that era spent at least a year and sometimes several years of their initial careers based on the watersheds. In a UNESCO (1983) report on experimental experience in water resources education the necessity of experimentation for theoretical understanding is stressed. The report further states that "the gathering of data should be a well organized activity with a great deal of responsibility involved." These points should not be lost in future experimental watershed efforts or on future ARS scientists.

Methods of Analysis and Improvement

Modernization of all ARS experimental watershed by installing electronic datalogging equipment is a obvious way to improve the existing data collection program. Many of the experimental watersheds have or are already in the process of making this conversion. Conversion to datalogging equipment has its own inherent difficulties and 100 percent data capture is not guaranteed with this equipment. High speed INTERNET connections between experimental watershed research groups will serve several purposes in improving capabilities. Expertise in using new datalogging equipment and new instrumentation can and should be shared in a ARS Watershed E-mail bulletin board. High speed connections will facilitate large data transfers required to conduct inter-watershed data analysis and comparisons.

Research Opportunities

> *"The successful research person is the one who asks the right questions. Research must go on primarily in the mind and only secondarily in the physical and biological world."*
> *Leopold (1970)*

The existing ARS Experimental Watershed database, as well as the watershed instrumentation and support infrastructure afford unparalleled research opportunities. To fully grasp these opportunities, national, not individual location, objectives for the experimental watershed program must be set. The authors feel that a significant impact on the hydrologic sciences could be made if several national projects could be defined to conduct unified analyses of the entire ARS watershed network. But, as the statement by Leopold (1970) above points out, we must give thoughtful consideration of the research resources of the experimental watershed network and ask the right questions. The following questions are posed to help define significant research opportunities.

1. Can existing data from the nested watersheds present in many of ARS watershed locations be utilized to define the dominant hydrologic processes as a function of basin scale and perform inter-basin scale analyses across the major climatic regions represented by the watersheds? If the dominant or controlling processes can be defined as a function of basin scale and climatic region, both the data collection and modeling efforts can be focused and associated and economies be realized.

2. By conducting a unified time series, and spatial correlation analysis of rainfall-runoff data in the existing ARS database for all watersheds can:

   a. Long trends that may be the result of anthropogenic change be identified?

   b. Insight into the duration/cycles of floods and drought be acquired?

   c. Design criteria to enhance water supply and minimize flood damage for local agricultural and engineering planning communities be improved?

   d. Guidance and assistance be provided to agriculture to help it survive on the urban fringe where large cities may have altered the hydrologic regime?

3. Can the ARS further the science of land-atmosphere water and energy interactions by coupling hydrologic, energy, and atmospheric boundary layer measurements (including remote sensing), and by conducting interdisciplinary field campaigns over a variety of ARS Experimental Watersheds (such as MACHYDRO '90 over Mahantango, MONSOON '90 over Walnut Gulch, and the 1992 campaign over the L. Washita)? Conducting such experiments will facilitate and require interagency cooperation and offers an excellent opportunity to expand to larger watershed areas and to develop methodologies for aggregation and disaggregation across plot to watershed to basins scales (to 10^5 km^2).

4. Can the ARS quantify and predict the magnitude of groundwater/surface water interactions with existing and new measurements in experimental watersheds in both influent and exfluent channels (losing and gaining streams)?

5. Can small scale, economical measurement techniques be developed to obtain large area representative estimates with associated variability estimates? In many current model applications, variable and parameter estimates are derived from data collected at one scale and are misapplied in the model as representative for a much larger scale. In addition, concepts to measure sediment transport and concentration are 40-50 years old. Can new concepts and associated measurement instrumentation be developed or can we adapt new emerging technologies developed by other to local watershed conditions?

6. Can experimental watershed data and facilities be used to verify important water quality mitigation strategies such as filter strips, riparian reclamation, and constructed wetlands for water detention and cleansing in cooperation with SCS, EPA, and USGS? From a national perspective, how much uniformity in data collection is needed to test hypotheses, mitigation strategies and models? This is important as many regulatory agencies want methodology that applies nation-wide versus regionally.

In addressing any of the above research opportunities it is also important to quantify the uncertainty associated with measurements and predictions. To enable risk assessments to be incorporated into analyses it is necessary to have the ability to put confidence bounds around projections.

Conclusions

The ARS experimental watershed network was developed on the backs of many outstanding and dedicated scientists and technicians. Their vision, dedication, and associated research have resulted in many pivotal contributions to agricultural sustainability and hydrologic science. This group deserves special thanks for the treasure they have endowed to the future ARS Experimental Watershed Program. With this treasure comes commensurate responsibility to sustain and improve this program. Given the current and projected fiscal climate, efforts must be re-double to utilize the network to its fullest extent and fully integrate it into research efforts. The ability must be maintained to strike a balance between long term data collection and flexibility to meet new program needs. Research goals must be broadened from a location or individual watershed perspective to a national network perspective. A great deal will be gained by an integrated, national analysis of data from the experimental network. However, the ability to ask the right questions will be a paramount factor in gaining the utmost benefit from the ARS Experimental Watersheds. Kelly and Glymph (1965) recognized this fact early in planning ARS experimental watershed research in the temptation to try to solve all problems. This may not be realistic as instrumentation to study one set of objectives may be far different than required for another set of objectives. "The point emphasized here is that careful and thoughtful planning should precede initiation of studies on experimental watersheds. Careful consideration should be given to limiting the objectives of research to those for which resources are available - this on the theory that it is better to do a few things well than many things badly" (Kelly and Glymph 1965). Good advice from wise predecessors that all should heed.

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Table 1. Characteristics of Active ARS Watersheds (based on Jan. 1, 1991 figures, from DeCoursey (1992).

Size		Length of Record		Primary Land Use	
Hectares	No.	Years	No.	Type	No.
< 4	58	< 10	20	Crop	30
4 - 40	28	10 - 20	30	Pasture/Range	59
40 - 405	20	20 - 30	42	Mixed	46
405 - 4050	19	> 30	48	Meadow	1
> 4050	15			Pasture/Meadow	3
				Woodland	1

Table 2: Critical Measurement and Information Gaps in the ARS Experimental Watershed Network

Measurement or Information Gap	Related Auxiliary Meas./Information
Energy/radiation balance measurements	Direct evapotranspiration estimates
Basic suite of water quality/erosion Meas.	Long term at the field and watershed scale
GIS database coverages in easily accessible format	Topography, soils (including hydraulic properties), land cover, stream networks, basin boundaries and instrument locations, impoundments, geology and stratigraphy
Remotely sensed measurements over a variety of scales	Multi-spectral data at ground, aircraft and satellite altitudes
Distributed ecological/biomass Meas.	Microbial activity with depth
Biogeochemical balance measurements	Primary nutrients and evolution of greenhouse gases
Distributed, internal water, energy and sediment flux measurements	Required to verify distributed models
Paleo measurements to correlate and identify long term trends	Tree ring analysis, cosmogenic soil dating, etc.
Historical and descriptive Information (Metadata)	Track and document land use and instrumentation changes with assessments of data quality and uncertainty estimates

Figure 1. Location of active and closed ARS watersheds as of January 1, 1992.

Geographic Information Systems and Large Area Hydrology

J. G. Arnold[1], J. D. Garbrecht[2], and D. C. Goodrich[3]

Summary

Large area water resources development and management require an understanding of basic hydrologic processes and simulation capabilities at the river basin scale. We define large areas as river basins of thousands or tens of thousands of square kilometers. Current concerns that are motivating the development of large area hydrologic modeling include climate change, management of water supplies in arid regions, large scale flooding, and offsite impacts of land management. Recent advances in computing hardware and software have allowed large area simulation to become feasible and have uncovered current limitations as well as opened up new challenges and opportunities.

A Geographic Information System (GIS) application in large area hydrology requires a finely tuned integration of three major components: a GIS, a database, and a hydrologic model. Databases exist for the entire U.S. that are required for hydrologic assessment such as soils, land use, topography, weather, and streamflow records. These databases all have limitations with regard to hydrologic modeling. A major challenge is to select or formulate a hydrologic model that is compatible with the limitations of existing databases and is consistent with the spatial and temporal resolutions of the available data. GIS are being coupled with hydrologic models to extract model inputs from map layers and to spatially display model outputs. Three categories of GIS and model coupling are: 1) input/output using GIS and an independent model, 2) quasi-coupling with a largely independent model, and 3) complete coupling with hydrology functions imbedded within a GIS framework. Current research is largely focused on GIS coupling for small watersheds and a major challenge is to address coupling issues that are unique to large area modeling.

Major challenges in simulating large river basins include describing micro and mesoscale variability, simulating surface and groundwater interactions, addressing the spatial variability of rainfall, and linking to coarser resolution global circulation models. Current research in large area hydrologic models is focusing on developing continuous time models with finer and more flexible discretization capabilities. Is this the direction to follow, or do we need a new modeling approach for large watersheds? Research suggests that simulation of all microscale processes (.1-1 m) may prove impossible and unnecessary at the basin scale. We need a better understanding of the major hydrologic processes operating at the basin scale, and we need to continue research on integration of GIS, databases, and models.

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[1] Agricultural Engineer, USDA-ARS, 808 East Blackland Road, Temple, TX 76502.
[2] Research Hydraulic Engineer, USDA-ARS, P. O. Box 1430, Durant, OK 74702.
[3] Research Hydraulic Engineer, USDA-ARS, 2000 East Allen Road, Tucson, AZ 85719.

Introduction

There are several recent developments in computing hardware and software that are allowing large area hydrologic simulation to become feasible. These advances include:

- *Computer Speed.* Although computer speed has increased dramatically in recent years, so have the computing requirements of large area hydrologic models. Processing large databases and running continuous time, distributed parameter hydrologic models require considerable computer time. Desktop workstations are available that can process programs at 20-200 mips (million instructions per second) with data flow ranging from 30-80 megaflops (floating point instructions per second). Supercomputers are available through many universities and federal national research labs that are several orders of magnitude faster. Also, research is continuing on parallel processing and executing existing models in a parallel system. A parallel processing machine is currently available that contains1024 Sparc-based CPU's , 32 gigabytes of memory and 1 terabyte of quick storage. It can attain peak computational speed near 128 gigaflops (1,000,000,000 floating point operations per second), which is approximately 1000 times faster than a desktop workstation.

- *Computer Storage.* Desktop devices are available that can store over 20 gigabytes of data and compact laser disks are common that can be shared by users that hold up to 650 megabytes. This technology is barely keeping pace with the data generated by satellites.

- *Computer Networking.* The UNIX operating system is being used at many research locations to link scientists within a lab and with Internet access, to allow communication between scientists at research locations around the world. This link can speed multilocation model development and allow databases to be stored at a centralized location and be easily accessible by anyone on the network. A wide range of communication links exist to transfer data ranging from 300 baud using telephone modems to 1 gigabyte per second using Hi-performance Parallel Interface Technology and fiber optics.

- *GIS/Spatial Analysis Software.* The advent of geographic information systems are playing an important role in large area hydrologic simulation. The role of GIS will be discussed in detail later in this paper.

- *Software Debugging Tools.* The recent development of advanced code debugging tools has allowed more rapid development and verification of complex simulation models.

- *Visualization Software Tools.* Large area hydrologic models generate overwhelming volumes of output and software tools are being developed to easily visualize and analyze model inputs and outputs.

State-of-the-Knowledge

Current state-of-the-art in large area hydrology has been significantly influenced by the previously presented advances in computing. In the past, large area models have been limited by the resources (time, personnel, and expense) required in obtaining input data and by the intense computational requirements. Consequently, a trade-off has occurred between spatial and temporal resolution. Distributed parameter models allow a basin to be subdivided into small subbasins. Because of the extreme spatial complexity, these models have until now been limited to single storm events. On the other hand, continuous time models have not allowed the basin to be subdivided as finely and

some lumping of inputs is generally required. Advances in computer hardware, combined with spatial data handling systems, such as geographic information systems, are attempting to overcome these limitations. Current research has focused on developing continuous time, distributed parameter models, linking surface and subsurface flow models, developing models that allow greater flexibility in watershed discretization, and developing more modular modeling frameworks.

Geographic Information Systems are designed to store, manipulate, and display geographic information such as maps of soils, topography, landuse, and landcover. There are different ways of describing what a GIS is and what it does. One is to consider it a database (realizing of course that it is much more) that can be utilized by various models and tools. A single GIS for non-point source pollution control can facilitate multiple applications: effectively pinpointing areas where resources are threatened, helping impartially distribute incentives and regulations used for rural land management, providing quality information to decision-makers cost-effectively, and speeding the delivery of conservation services. One function of many of the GIS that have been developed to date is erosion control planning. Simple erosion prediction models such as the USLE are easily implemented within most GIS tools. There has recently been considerable effort in utilizing GIS to extract inputs (soils, land use, and topography) for comprehensive simulation models and spatially display model outputs. Much of the initial research was devoted to linking single-event, grid models with raster-based GIS (Srinivasan and Engel 1991, Rewerts and Engel 1991). Research is also continuing on utilizing GIS as an input/output interface tool for continuous time models using subwatershed boundaries based on natural flow paths (Sasowsky and Gardener 1991, Srinivasan and Arnold 1993).

The new opportunities created by the advances in computing are creating new areas of critical research in large area hydrology. The opportunities have allowed us to see several shortcomings in existing technologies that will be discussed in this paper:

- Adequacy and quality of the databases.

- Limitations and potential of existing hydrologic models to simulate large river basins.

- Limitations and opportunities for coupling GIS to hydrologic models.

Scientific Challenges

Three main areas of large area hydrology are discussed in the following including large area databases, coupling GIS and hydrologic models, and large area models. Limitations, critical gaps, and knowledge deficiences are addressed.

Large Area Databases

Selected data-base related problems in large area hydrologic applications using a GIS are reviewed in this section. For the purpose of this discussion, large area is defined as any watershed exceeding several hundred square kilometers. The practical aspects, necessity and advantages of a GIS as the data preparation, management and display environment are assumed to be known to the reader. The hereafter presented data-base problems are not intended to dispute the capabilities or question the necessity of using a GIS to conduct large area hydrology. They aim to focus on opportunities and challenges in large area hydrology.

A GIS application in large area hydrology requires a finely tuned integration of three major components: a GIS, a data base, and a hydrologic model. Each of these components are briefly reviewed and fundamental problems in their integrated use in large area hydrology, especially with respect to data bases, are discussed thereafter.

Geographic information systems. A GIS is a tool that is primarily used to manage, manipulate, process, overlay and display spatial data. It performs data preparation tasks that were traditionally done manually or by semi-automated procedures and visualizes intermediate and final output data. The GIS can display individual spatial data layers, combine and display a variety of data layers, or perform data processing functions on data layers and display the results. These tasks are performed very efficiently and the colorful graphical displays are highly sophisticated and informative. It should nevertheless be remembered that the quality of the results (display) are not related to the GIS capabilities, but to the quality of the initial data input into the GIS. This aspect is often overshadowed by or even forgotten amid the sophisticated and fanciful GIS manipulations and displays.

Data-bases. Topography, hydrography, soils, vegetation and climate over the geographic region of interest are basic spatial data needed in large area hydrology. Other data may be also be necessary. However, within the limited framework of this paper, only the ones listed above will be treated. Field collection of this data is generally impractical, if not impossible, and existing data sources are used to the extent available. This USGS Digital Elevation Model (DEM) data is often used for topographic data, mainly because of its extensive and consistent coverage. DEM elevation data are available in 7.5 minute, 15 minute, 30 minute and 1-degree units. USGS digital line graphs (DLG) of elevation contours are also available for different map scales. Hydrographic data are provided by the USGS in DLG format. The data includes streams and water bodies. The DLG data for contours and hydrography are available for 1:24,000-, 1:100'000-, and 1:250,000-scale maps. Drainage boundaries are available in the 1:250,000-scale land use may series only. As an alternative, most hydrographic data can be extracted from DEMs using existing GIS software. Digitized soil survey data are available through the USDA-Soil Conservation Service. Three levels of digitized soils data exist in various levels of completion: 1) national soils map (NATSGO, 1:2,000,000; completed), 2) state general soil maps (STATGO, 1:250,000; mostly completed), and 3) county soil survey maps (SSURGO, 1:24,000; mostly complete). The SCS is in the process of digitizing this SSURGO data. The digitized soil surveys, used in conjunction with a soils attribute data base (Soils-5), define the spatial distribution of soil characteristics. Land use and land cover data show seasonal character, and, particularly in agricultural regions, it may change as a result of human intervention. An up-to-date land use/land cover/albedo data are derived from the AHVRR (Advanced Very High Resolution Radiometer, NOAA-11) 1-km imagery. The data is available at different resolutions (LAG 1 km; GAC 4 km; GVI 16 km). A vegetation index is used to define the land use and cover classes. With two readings a day the dynamics of the vegetation cover in time can be captured (Loveland et al. 1991). Finally, climatic data can be obtained for national weather service stations, and from climate generators, satellite or radar (precipitation only). Even though most fundamental data appears to be available in one form or another, inherent limitations make their use in large area hydrology problematic. A few selected problems are presented in the following.

The USGS 7.5 minute DEM data is obtained by one of four procedures: (1) the Gestalt Photo Mapper II, (2) manual profiling from photogrammetic stereomodels, (3) stereomodel digitizing of contours, and (4) derivation from DLG hypsography and hydrography categories. Three levels of DEM data are available. The higher the level the more accurate the elevation data. The accuracy

standards for the three DEM levels can be found in USGS (1990). DEM data acquired by procedure (1) and (2) are restricted to the level 1 category. These procedures were used in the 1970's and early 1980's, and a good portion of the USGS DEM 7.5 minute data falls in this category. This data contains systematic and recognizable errors within stated limits of tolerance that make this data generally unusable for drainage and hydrographic analyses. For example, the manual profiling results in striping along the profiles that can interrupt flow paths, create artificial depressions and alter drainage boundaries. DEM data acquired by procedure (3) falls usually into the level 2 category and represents todays standard procedure. This data has been processed or smoothed for consistency and edited to remove identifiable systematic errors. It is of higher quality then the level 1 data, but its suitability for drainage analyses remains to be tested. Finally, level 3 DEM 7.5 minute data, the highest quality, is not produced on a regularly basis at this time. Therefore, caution should be excerised using the USGS 7.5 minute DEM data for drainage applications, in particular when it is used to derive hydrographic data and for flow routing.

The SCS county soil surveys are generally used as a source for soil classification and spatial distribution. The clear cut boundaries between soil classifications, as shown on the soil surveys, rarely exist in the natural enironment. Spatial transitions between soil characteristics are gradual. It is also noted that soil classification and the determination of the boundaries between soils is not an exact science and depends to some extent on the experience and interpretation of the soil scientist. Given these considerations, inconsistencies in soil classification between counties may exist. In GIS displays, these inconsistencies become particularly apparent along county boundaries. The application of the soil surveys in hydrologic investigations requires that specific soil properties be known. In large area hydrology the number of soils does not lend itself to conduct on-site measurements. The general approach is to access a soils database which contains the parameters for each soil. Soils-5 is the database often used. This data base, however, provides a range of values for each parameter and the appropriate parameter value remains to be determined. Furthermore, it is noted that the soil properties are generally given for the B-horizon, yet the A-horizon may be determining soil horizon for the hydrologic processes. For example, in semi-arid climates the runoff separation for high intensity, short duration, precipitation events is generally controlled by the top soil horizon.

The land use and land cover data is very important in large area hydrology, particularly when the effect of regional land management changes are being quantified. The AVHRR data which is used to determine land use/cover is evaluated at five different levels of detail. Level 1 land cover data provides the basic grouping of the vegetation (agriculture, range, forest, water barren, etc.). Level 2 data provides subgroups of each vegetation group. Higher levels provide more detailed groupings. To the best knowledge of the authors, level 3, 4, and 5 are not available at this time. It is likely that the currently available data is not sensitive enough to distinguish subtle changes in land use/cover induced by agricultural management, or between different crops having similar reflectivity. Other problems with AVHRR data include the distortions resulting from off-nadir viewing and pixel elongation at the edge of the image, as well as the ground-truthing and interpretation of the data at the available resolutions.

Finally, spatially distributed precipitation datasets for large area hydrology are not easy to obtain. The national weather service stations are generally many miles apart. In mountainous areas the stations density is particularly low, and localized orographic effects generally prevent the data from being applied to a wider area. The overall low station density results in poor interpolation of rainfall fields between stations. Local convective storms between stations remain largely unmeasured. Weather generators are available to estimate daily point precipitation values.

However, practical generators that provide good spatial precipitation distributions over large areas and reproduce the dynamics of frontal movements remain elusive. Satellite data (GOES, NOAA) can be used to determine cloud density and moisture content, but a reliable procedure to infer precipitation on the ground is not available. The best source of precipitation data for large areas is the doppler radar data that will be available in the near future.

The above examples are illustrations of uncertainties and approximations in large area data. Additional problems can be expected when combining the data because of the different resolutions at which individual data items are provided. Little can be done about the quality of the data, and large area hydrology will have to deal with the data limitations.

Hydrologic models. Physically based, conceptual or empirical numerical models are generally used to simulate the hydrologic watershed processes. Physically based models solve equations describing the physical processes. They are complex, yet widely applicable and transferable. They also require detailed input data. Due to date uncertainties and natural variability some calibration may be necessary. Conceptual models are simplified representations of the physical processes. Their widespread use reflects the inherent complexity of the hydrologic processes and the practical inability to account for all aspects of these processes. They are less data intensive then the physically based models and require some calibration. Finally, empirical models are the simplest of all modeling approaches. They emphasize key parameters on which the solution is based. They require calibration and can only be applied over the range of conditions for which they are calibrated. Given today's powerful computers and GIS capabilities, the preferred approach to large area hydrology appears to be distributed modeling using physically based or conceptual models.

Even though a GIS is capable of managing the data and modeling environment, and even though fundamental data and hydrologic models are available, the integration of all three components into one consistent modeling unit for large area hydrology is a significant challenge. For example, the GIS can represent and overlay data and corresponding boundaries with great precision, yet data uncertainties and approximation do not warrant such a precision; or, physically based models can be applied to small subwatershed areas and the GIS can discretize a large area into many subwatersheds, yet data availability and quality limits the resolution of the discretization and the use of this approach. The use of GIS, databases and hydrologic models for large area hydrology must address the issue of compatibility between the three components and must assess the reliability of the modeling results.

Challenges. The challenge is to select or formulate a hydrologic model compatible with the limitations of existing databases and that can be operated at spatial and temporal resolutions that are consistent with the available data. This includes operating the GIS within the range of spatial resolutions dictated by the model and the databases, and to account for the fuzzy nature of many of the data layers. The hydrologic model and the resolution at which they are applied must be sensitive to the dominant processes and spatial variabilities that control the hydrology of large areas.

Research opportunities. 1) Determine of dominant hydrologic processes at the large scale. 2) Determine of the spatial and temporal resolution at which dominant large scale hydrologic processes operate. 3) Formulate a hydrologic model for the dominant hydrologic processes that will operate at the resolution of these processes, that can operate within the limitations of the available data, and that is insensitive to small scale data uncertainties. 4) Modify the GIS to account for fuzzy data layers, and formulate guidelines to operate the GIS at resolutions that are compatible with model and database limitations.

Coupling GIS and Hydrologic Models

To fully apply the power of GIS to large area hydrologic modeling a fully coupled GIS/Hydrologic modeling system must be developed. Without true coupling our hydrologic modeling efforts will never fully reside within a GIS and a good deal of both computational and research effort will be expended in the back and forth from model to GIS. The move toward coupling is not solely on the shoulders of the hydrologic community as many GIS implementations are already incorporating hydrologically oriented capabilities. It is more likely that the two groups will meet somewhere in the middle. Within this section three classes of GIS and hydrologic model coupling are discussed as are concerns with the use of digital elevation data and large area applications.

Three classes of GIS and hydrologic model coupling can be roughly categorized as: 1) Input/Output using GIS with an independent hydrologic model; 2) Quasi-coupling with a largely independent hydrologic model, and; 3) Complete-coupling with hydrology functions imbedded within a GIS framework. The first class of coupling was alluded to earlier where definition of hydrologic model inputs or parameters for models such as the USLE (or RUSLE) are defined in a largely off-line manner using a GIS. In the case of an independent distributed model, a GIS is often used in the first class of coupling for input and to display and visualize model output. A variety of hydrologically oriented GIS functions are available in the more robust GIS programs to aid the hydrologic modeler in defining typical inputs. They include basin and stream network delineation as well as slope and aspect definition from digital elevation model (DEM) data, and spatial averaging of cover and soil parameters.

In the second class, a quasi-coupled GIS/hydrologic model depends much more heavily on GIS for not only input/output definition but for tracking state variables and parameter updates during the execution of the hydrologic model. The hydrologic model is this class could still be run independently of the GIS. However, substantial programming and database manipulation efforts would be required to organize and keep track of distributed watershed information that a GIS can easily handle. An example of this quasi-coupling is discussed in Gao et al. (1991). They used the GRASS GIS with a 2-D surface/near surface hydrologic model coupled to a 1-D shallow groundwater model. DEM data and associated GIS functions were used extensively in this model as equations of continuity and momentum were solved via finite difference methods. In addition to input/output and data organization typical of the first class of coupling, Gao et al. (1991) used the GIS for real time, distributed water flux visualization and iterative tracking of state variables required for subsequent computations.

Examples of truly coupled, physically based, GIS/hydrologic models are not available. For simple conceptual or regression based hydrologic models, the computations required can be performed within a grid-based GIS using map algebra. Map algebra allows a variety of mathematical operations on a grid-based GIS coverage layer or combination of layers much like a spreadsheet (imagine a grid GIS layer as a spatial spreadsheet). Map algebra continues to become more sophisticated and can even iteratively solve certain nonlinear equations, but it still has difficulty treating feedback from adjacent grid cells that may be encountered in topographically directed flow situations such as backwater.

Maidment (1992) provides a good discussion on methods and attempts to fully couple hydrologic models within a GIS framework. In his report, Maidment discusses important GIS network functions that are typically applied for routing in traffic and street networks in which a *Lagrangian* approach is used to track particles moving through a defined flow field. To couple models such as the KINEROS (Woolhiser et al. 1990) or the HEC series of models (HEC 1990) which simulate

flow through linearly connected flow components an *Eulerian* set of GIS network functions must be developed.

To overcome the *Lagrangian-Eulerian* conceptual mismatch Maidment (1993) advocates a hybrid grid-network approach in which a hydrologic modelling network can be imbedded in the 2-D landscape domain of a grid and connected with the 1-D domain of the stream network. In the grid domain, spatially varied processes of precipitation and infiltration can be treated. With basin segmentation provided by the stream network, data structures to get water from the sub-basin tributary areas to the stream network could be generated for a grid-based unit hydrograph or cell based kinematic wave model. Once water is routed into the stream network, more sophisticated reservoir or stream routing techniques could be used if detailed cross-sectional information is available. In summary, a variety of powerful GIS data manipulation and network functions exist to assist hydrologic modeling but additional research must be carried out to fully and efficiently integrate some classes of hydrologic models into GIS.

Digital elevation model and length scale considerations. A primary consideration in the complete-coupling class is the type of DEM data representation of the GIS. DEM data is particularly important for derivation of basin boundaries and stream networks within the GIS and for hydrologic models that perform finite difference or finite element based surface or near surface routing. The three primary forms of DEM data are regular grid data, triangular irregular networks (TIN), and contour string (vector) data. Moore et al. (1988b) provides an excellent review of these data types. The most common type of DEM data is regular grid data but some GIS packages allow conversion of various types of DEM data to each of the other forms.

From a GIS data storage and hydraulic routing standpoint, each type of DEM data also has its particular advantages and disadvantages. Regular grid (raster) data, although computationally convenient, suffer from poor definition of flow paths across grid cells, the inability of objective flow partitioning out of a single cell (Moore et al. 1988a), and digital data redundancy in smooth regions. As an advantage, regular grid DEMs are easily interfaced with most forms of remotely sensed and raster based data which are often used to represent soil, vegetation and land use information.

Contour based (vector) data enables the ready definition of streamtubes which allows routing computations to be completed as a series of one-dimensional coupled equations (Tisdale et al. 1986, Moore et al. 1988b). The chief disadvantage of contour based data is the large data storage requirement. Moore et al. (1988b) estimate that approximately one order of magnitude more points are required for comparable surface approximation using contour data than for regular grid data.

Routing on TIN DEM data requires a two dimensional approach due to the arbitrary orientation of TIN facets (Goodrich et al. 1991). This approach overcomes the problems of flow division and convergence when routing on a regular grid DEM. Because TIN DEMs typically require far fewer points to represent topography than regular grid or contour DEMs due to their "coordinate random, but surface specific" character (Peucker et al. 1978), substantial computational economy in routing is also realized. Routing on TIN's therefore represents a compromise between slightly increased computational complexity and the economy of TIN topographic representation.

Another important consideration in the coupling of hydrologic models to GIS is the need to adequately maintain characteristic length scales of the phenomena being modeled. In an attempt to adequately model fluxes represented by partial differential equations, numerical methods must maintain time/length scale ratios representing the characteristic length scale of the hydrologic

process being modeled to obtain accurate solutions. This may require imbedded GIS computational layers that have a finer grid resolution than the grid resolution of data layers typically stored in GIS such as soils and topography. Utilizing a very coarse resolution numerical grid may provide solutions after model calibration to observations. However, in this case, the model becomes more conceptual in nature and physically based interpretations will be difficult to justify.

In light of the large area database problems discussed earlier the application of physically based models which utilize conservation of mass and momentum concepts may be quite difficult. In this class of models, a high degree of parameterization and data input resolution is typical and accurate definition of driving gradients is crucial. It may be some time before database resolution and computational resources are available to support this level of model complexity. Improvements in both areas will continue to be made and research should therefore continue in coupling this class of models to GIS. In the near term (5 years) new modeling approaches will be required or it will be necessary to employ a more conceptual, less physically based hydrologic modeling approach to large area problems.

Large Area Hydrologic Models

The recent advances in computing power have initiated a trend in large area hydrologic modeling to discretize a basin into finer and finer subbasins. There is also current research that is allowing more flexibility in how a basin may be discretized (Arnold et al. 1993). Is the trend toward finer discretization the appropriate direction to head or should we develop an entirely new modeling approach? Recent research suggests that a new modeling approach may be required for large area hydrologic modeling.

Microscale vs. mesoscale. Woolhiser et al. (1990) describe two spatial scales. The first is the microscale with a characteristic length of 0.01 to 1.0 m. Microscale variability includes surface microtopography, micro areas of ponding, variation in hydraulic conductivity, and distribution of chemicals in the soil. The complexity of microscale processes related to field transport of dissolved materials suggest that solute movement over basin scale distances are best described as random (Rodriguez-Iturbe and Valdes 1979, Gupta et al. 1980, Gupta and Waymire 1983). Rinaldo and Marani (1987) concluded that large scale simulation of all microscale processes may prove impossible and may also be unnecessary. Mesoscale distributions (10 to 10000 m) relevant to basin scale response are independent of the detailed form of the interactions operating at the microscale. Woolhiser and Goodrich (1988) used a kinematic cascade model to account for microscale and mesoscale spatial variations. Mesoscale variations were accounted for by subdividing the watershed into planes with each plane having a mean and coefficient of variation of saturated hydraulic conductivity (K_s) values. To account for microscale variations, they also subdivided the planes into subareas with K_s equal to the median value of equal probability intervals of the cumulative K_s distribution which was assumed to be lognormal. The analogy is that each plane element in a catchment consists of independent parallel planes with different K_s. They concluded that both spatial scales appear to be important.

Surface water groundwater interation. Basin scale water resources development and management plans require quantification of the major components of the hydrologic balance including surface runoff, groundwater flow, impoundment storage, plant uptake, consumptive use, and depletion of groundwater by pumping wells. In most previous groundwater modeling applications, recharge is estimated by empirical methods which have limited application to the impact of surface management. Also, most surface modeling applications assume percolation from the soil profile is lost from the system and ignored. Several attempts have recently been made to

link surface and subsurface models (Chiew and McMahon 1984, Prakash and Jafari 1987). However, most attempts have not included the ability to simulate management impacts such as cropping systems, tillage, reservoirs, and climate changes.

In order to achieve a complete coupled description of water movement in surface and groundwater flow, a series of information is needed for the surface, the soil profile, and various subsurface strata. It is possible that these layers can be constructed in 2-D but arranged vertically above one another using a terrain network that has a common set of x,y coordinates for all layers, but each layer has a vertical location and descriptive attributes (Maidment 1992). If surface and groundwater models are to be linked, a true 3-D representation is the ultimate configuration. Although this may be technically feasible, the detailed spatial data bases needed to drive a 3-D model for large basins is not available. Detailed soils, geology and vadoze zone maps and related properties are not readily available for large river basins and simplier models of surface-groundwater interactions will need to be developed (Arnold et al. 1993).

Rainfall spatial variability. One of the major limitations to large area hydrologic modeling is the spatial variability associated with precipitation. There are over 8000 raingage locations in the U.S. with over 30 years of daily precipitation data. There are on average two or three gages per county which leaves several kilometes between gages. This can cause considerable errors in runoff estimation if one gage is used to represent an entire subwatershed or even if an attempt is made to "spatially weight" precipitation for a subwatershed. Also, the data files are difficult to manipulate and contain considerable days of missing records.

Weather generators can be extremely useful when measured data is unavailable and management scenarios are being compared. Daily weather generator parameters are available for generating weather sequences at a point, however, spatially correlated generators required for large area hydrologic simulation have not been developed. The physical processes driving large area weather phenomenon are not fully understood and many technical obstacles need to be overcome before spatially correlated rainfall generation is possible.

Another possibility is to utilize the WSR-88D radar technology (formerly called NEXRAD - Next Generation Weather Radar) to measure aerial precipitation rates needed to drive large area hydrologic models. ARS researchers at Durant, Oklahoma are currently testing WSR-88D and are simulating runoff based on WSR-88D estimates of precipitation.

Linking to global climate change models. Several global climate models exist and the predictions of these models on global warming concern hydrologists that such warming may impact the hydrologic balance. Of particular concern are droughts, flooding, and the possibility of rising sea water levels that could inundate coastal lowlands. Global circulation models are built on a square grid with each cell side hundreds of kilometers long while modeling subareas for hydrologic models are much smaller. One way to overcome this may be to aggregate fine-scale components up to some optimum level where interaction between fine and course scale information can occur (Rastetter et al. 1992). Recent research in this area is encouraging in that it appears that complex spatial patterns in plant physiology and in hydrologic processes may be explained by simple models based on a few principals (Schimel et al. 1991, Running and Nemani 1992).

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Spatial and Temporal Variabilities of Landscapes

D.D. Bosch[1], K.S. Humes[2], F.B. Pierson[3], and M.A. Weltz[4]

Summary

The task of characterizing spatially and temporally varying landscapes is a large one. Scientists have made progress in the past 20 years: first in recognizing that spatially variability must be incorporated into hydrologic models, and second in quantifying variability associated with input parameters for these models. To better model variable landscapes we must first understand the role played by heterogeneity.

> *"We can have no hope of understanding determinate heterogeneous systems unless we first understand homogeneous ones, and to take this further, we shall have no hope of understanding stochastic heterogeneous systems without first understanding determinate ones." (Philip 1980)*

Our current ability to predict how geophysical properties vary over space and time is very limited. A related issue concerns our current inability to control or quantify errors associated with measurement techniques themselves. This document represents an attempt to address these issues and set a research agenda for the future. The current research status was evaluated, gaps and problems were identified, and promising areas were defined. Scientific challenges identified include:

1) determining the scale at which current research should be focussed;

2) developing better methods for incorporating spatial variability into models and their estimates;

3) establishing better methods for extrapolating between the scale at which parameters were evaluated and the scale at which they are applied; and,

4) developing better methods for characterizing spatial variability.

Associated research opportunities established were:

1) relating hydraulic properties to vegetation type and other methods of indirect parameter estimation;

[1] Hydraulic Engineer, USDA-ARS, P. O. Box 946, Tifton, GA 31793.
[2] Hydrologist, USDA-ARS, Building 007, Room 104, BARC-West, Beltsville, MD 20705.
[3] Hydrologist, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[4] Hydrologist, USDA-ARS, 2000 East Allen Road, Tucson, AZ 85719.

2) evaluating the significance of temporal variability in hydrologic processes;

3) expanding applications of remote sensing;

4) improving methods for analyzing large data sets; and,

5) planning more integrated research projects.

It is important to understand soil-physical processes including spatial variability so that appropriate theory is used in hydrologic models. We must continue our efforts to elucidate the complications which form the gap between what is found in the field and what our simplified mathematical models are capable of representing.

Introduction

Geophysical variability is apparent both on the land surface and the subsurface. Tectonic, sedimentary, and cultural processes produce the landscapes in which we currently do our hydrologic research. Sedimentation associated with streams and lakes is a dynamic process. Sediments are deposited and eroded over time, leaving behind a vast array of particle arrangements. Tectonic forces shift deposited sediments and bring to the surface subsurface materials. Overlain on this are soil formation processes which affect the surface geologic material in which we have traditionally confined our research. Cultural processes associated with agriculture also has a significant effect on the landscape.

Although interesting from a scientific perspective, the primary reason for studying geophysical variability is to establish order and predictability. The first step in developing a model which mimics a natural system is establishing a conceptual understanding. This is based upon an understanding of how the system reacts to variability and how components interact. Once we understand these interactions, mathematical relationships can be formulated, following rules and requiring inputs. It is in establishing these inputs that variability must be quantified.

> *"At its present level of development, soil-water physics provides quantitative physical theory and quantitative measurement techniques which enable useful quantitative predictions about the equilibrium and movement of soil-water, and of material in solution in soil-water, under certain circumstances. These circumstances are those of controlled experimentation on laboratory systems which are not too complicated and of simple field situations. Difficulties frequently arise, however, when attempts are made to apply quantitative soil-water physics over areas of any size in the field." (Philip 1980)*

In the 13 years following this statement, some progress has been made in evaluating field and watershed scale phenomena. However, our models are still not and may never be absolute predictors of hydrologic responses. The dominant reason for our inability to jump from the controlled laboratory settings to "real" field conditions is variability of landscapes, both in time and space.

Variability poses special problems in the collection of data to be used as input for or the testing of physically based models. Measurement techniques assume soils to be uniform in the region of measurement. If heterogeneity is present, the measurement gives some equivalent value appropriate

for the measured area. This equivalent value may not be relevant for modelling the field situation for which the measurement is taken.

All porous materials are inherently heterogeneous when viewed at a small enough scale. Also, in the case of simple porous systems of uniformly packed particles, heterogeneity gives way to an apparent homogeneity so far as physical properties are concerned as the scale of viewing increases. This scale is referred to as the representative elementary volume (REV). It is on the basis of this apparent homogeneity at a large enough scale that soil physical "constants" are defined.

Field measurements are best made with the application in mind. For example, if the objective is to predict runoff from a field sized area using the field as the computational unit size, then one would desire to know the set of inputs which best represent the field as a whole and not individual locations on the field. However, traditional field methods have been technique driven rather than application driven. The area over which the measurements are taken often depends more on available techniques than on how the data will eventually be used.

Soil heterogeneity may be deterministic in that it is known and can be measured, or stochastic in that it varies randomly. However, spatial variability is, in general, not purely random. If measurements are made at two different locations, the closer the measurement points are to each other, the closer the measured values will generally be. Normally, there is correlation in the spatial distribution of measured data.

Some classical methods which have been used to evaluate variability are statistical, geostatistical, and stochastic. Classical statistical methods involve estimation of a mean, a variance, and a distribution. We assume the estimate we obtain through sampling accurately reflects the population. However, we rarely collect enough data to establish precise estimates. Geostatistical methods also yield estimates of the mean, variance, and distribution, but in addition they evaluate correlation over time and/or space. The stochastic method assumes parameters associated with specific points in the system are random variables which can be characterized by statistical parameters (i.e., mean, variance, correlation lengths). Because of this definition, the stochastic method associates error estimates with predicted values. Difficulties with the stochastic method include evaluating the statistical parameters associated with inputs, determining how the results relate to the actual system, determining at what discretization level the parameters are to be applied, and the large number of samples necessary to evaluate the required input characteristics.

Scientific Challenges

Matching Measurement Scale to Problem Defined

The first challenge facing researchers and society alike is defining the scale of the problems being addressed. Philip (1980) raised this question:

> *"Can it be that the vast labor of characterizing these systems, combined with the vast labor of analyzing them, once they are adequately characterized, is wholly disproportionate to the benefits that could conceivably follow?"*

To avoid wasted effort we must clearly evaluate our goals and objectives, and use these to define relevant research related to variability.

Solving problems at the field scale requires different knowledge of variability than does solving problems at the watershed scale. The nature of current issues requires research at various scales. For example, the importance of hydraulic conductivity determined using a 20 cm^2 core becomes lost at the watershed scale. What is needed is a representation of hydraulic conductivity at the computational scale being used. In order to apply measurements taken on scales smaller than those at which they are applied, we need to better examine scaling relationships and model sensitivity.

There are many surface and subsurface models currently available. Each of these models has strengths and weaknesses. Each of these models was developed for application at a specific scale. We as modelers must take care not to overextend the intended use of these models. A better effort must also be made to ensure that regulatory and action agencies do likewise.

Distributed deterministic models require estimates of inputs at different scales. It makes little sense to be concerned with spatial variability measured within 1 m^2 plots when the model is using 10 ha grids. Examination of the sensitivity of the model to input variation becomes a very important issue in evaluating the importance of spatial and temporal variability of geophysical data.

Modeling

Several methods exist for incorporating variability into models. Models can be classified based upon the character of the results they produce. If any of the variables in the model are random having distributions in probability and are treated as such within the model framework, then the model is stochastic. If all of the variables are treated as constants, then the model is deterministic.

Some models incorporate characteristics of both of these methods in an attempt to combine some of the advantages of both approaches into one model. In this approach, the physically-based governing equations for a problem are simplified and one or several of the key parameters are treated as stochastic variables (Entekahabi and Eagleson 1989). However, as with other approaches, difficulties associated with scale and parameter development remain.

The most common modeling method is deterministic. Deterministic models assume a level of homogeneity. To a certain extent the system is assumed to be spatially and temporally homogeneous such that it can be described by a single set of constant inputs. Distributed models assume homogeneity over a defined computational scale. Traditionally, modelers have used mean estimates as model parameter inputs. However, in some situations use of the mean parameters may not yield reliable results.

A typical model validation involves taking numerous field measurements in order to get input parameter estimates. In conjunction with this, measurements are made to compare to model predictions such as runoff, soil-moisture, and chemical concentration. A judgement must be made on how to use the parameter estimates and how to compare model estimates to observed values. Do we use the arithmetic mean of observed values and compare it to the model output based upon estimates obtained using arithmetic mean values of the input parameters? Do we compare individual point observations to model estimates made using point measurements of the input parameters?

Hydrologic modelers must begin to include the variability of input parameters in their simulations. This will help to quantify model uncertainty associated with inputs versus uncertainty associated with the model itself. One method for doing this is Monte Carlo simulation. Monte Carlo simulation requires random samples from a distribution of input parameters, and generates a distribution of outputs. Statistical properties of the outputs are tabulated as desired.

Stochastic modeling places emphasis on the statistical characteristics of hydrologic processes. Stochastic methods can be used to incorporate the uncertainty of input parameters into model output. Purely stochastic models have been developed for simulation of saturated (Freeze 1975) and unsaturated groundwater flow (Yeh et al. 1985), for ground-water quality modeling (Duffy and Gelhar 1985), and surface water flow and transport. However, stochastic models have inherent problems. In order to establish a stochastic model of a complex hydrologic system many simplifying assumptions have to be made concerning the statistical characteristics of the input parameters. These assumptions decrease model accuracy. Second, data sets for establishing the statistical characteristics for the input are incomplete. Most available data sets are from too short a time period to establish a probability distribution with any degree of confidence. Each of these problems must be overcome in order for stochastic methods to offer more utility in general hydrologic modeling.

New Approaches for Measuring/Characterizing Variability

If we are to incorporate spatial and temporal variability into our modeling efforts, we must strive for consistency in our data bases. This means establishing standard techniques for measuring physical characteristics as well as developing new methods for obtaining data. This will allow us to more accurately compare data sets.

In addition to a standardization of techniques we must report sources and estimates of measurement error. It is critical to know the error associated with measurement, recording, processing techniques and the variability of the reported data in order to attempt to separate model error, parameter variability, and measurement error.

An opportunity exists for developing better estimates of surface characteristics based upon remotely sensed data. Scale and resolution of this data are continually improving. The speed at which data can be collected and the scales over which it can be applied make it a tool which will help us quantify spatially variable properties. Some promising areas for application of remote sensing are in the evaluation of surface texture, surface moisture, land use, and land slope. Coleman et al. (1993) found significant correlation among spectral radiance data and sand, silt, clay, organic matter, and iron oxide content of surface soils. However, the amount of variance explained was quite low. Coleman et al. (1993) attributed this to the coarse spatial resolution (30 m) of the available data.

Research Opportunities

Data Collection

Work has shown that the variability in surface soil properties which influence infiltration, runoff, etc. are strongly correlated with variations in vegetation life form (Blackburn et al. 1992). Perennial vegetation can modify surface soil conditions and thereby control hydrology. Infiltration under shrubs can be 3 to 10 times that in the interspace between shrubs (Blackburn 1975). Therefore, opportunity exists to use vegetation to stratify variability in surface soil properties (Pierson et al. 1993). This could improve sampling efficiency and aid in data interpretation. More work needs to be done on scaling such information to field or watershed levels. Evidence also shows that plant community type may be a way to stratify soil and hydrologic variables on a larger scale, but little data is available to test this theory.

Some evidence has been presented which indicates that on some rangelands temporal variability is more important than spatial variability (Blackburn et al. 1992). Erosion is generally low on most rangelands, but conditions exist where extreme erosion can take place (Blackburn et al. 1990).

Little information is available to predict such temporal responses since its collection is much more difficult than spatial data.

Remotely sensed observations have the potential to provide fundamentally new parameters which can be derived from areally-integrated observations at various spatial scales. One exciting new challenge in the remote sensing area is to develop techniques for deriving new models and their associated parameters.

More work needs to be conducted on interpretations of remotely sensed data and on the development of new remote sensing techniques which are useful at a variety of scales. Approaches are being developed which are more accurate and provide data at smaller scales. Remote sensing is useful for model parameterization, but not necessarily for model validation or calibration. Therefore, field techniques for collecting data at appropriate scales to validate and calibrate models still need to be developed.

Data Analysis
One of the biggest limitations in analyzing spatial and temporal data is data management and manipulation. Handling and processing large data sets can be difficult and time consuming. ARS has many data sets, some of which are long term, which are virtually untapped because they are not well organized, error checked and/or available for a variety of scientists to use. In the future remote sensing data may run the same risk if we are not equipped to process and assimilate large data sets. GIS systems are being employed to aid in this area, but additional tools and approaches are needed. Many database management tools are already available and the discipline of information management is growing rapidly. ARS needs to stay abreast of new developments in these fields and put more emphasis on and provide more credit for data collection and management efforts. Without good data the field of hydrology will make little progress in the future.

Some are geophysical characteristics are more difficult to measure than are others. For example, basic textural characteristics of soils are relatively easy and inexpensive to measure. However, hydraulic conductivity is difficult to measure because it is hard to collect a good quality undisturbed sample, and it is difficult to obtain a good estimate through lab or field measurement. Deterministic or stochastic models may be able to estimate those parameters which are more difficult to measure with a reasonable amount of accuracy. Past efforts to do this have met with some success, but additional time and effort must be put into this area.

Integrated Research
The hydrology of even a small watershed is very complex and difficult to quantify. Many processes interact to produce an overall watershed response which spans plant, soil and hydrologic disciplines. Therefore, to attack even the smallest hydrologic problems, requires a multidisciplinary approach. Few groups of scientists in the world are as broad-based as the one found within the ARS hydrology effort. ARS scientists need to work together at all levels to address future problems in hydrology. However, the current structure of the ARS does not adequately promote and reward cooperative projects. Therefore, identifying future integrated research projects is hindered until the ARS designs a better way of accomplishing multidisciplinary objectives.

Several multi-disciplinary field experiments have been carried out in recent years which provide the unique opportunity to study the application of remotely sensed data to the derivation of fundamental new parameters and variables observed at different spatial scales (MONSOON '90, Walnut Gulch

'92, Washita '92, and HAPEX-Sahel). These efforts attest to the success that can be made through cooperative efforts involving scientists from several different backgrounds.

Modeling

Our ability to parameterize models is far behind our model development and data collection efforts. This is due primarily to an inability to quantify spatial and temporal variability at the scale of interest. More research and model development effort is needed on model parameterization techniques. This includes field data collection procedures that action agencies can use to collect data for model parameterization, calibration, and validation. We need better algorithms for estimating difficult parameters which incorporate spatial and temporal variability. We need to expand our research on artificial intelligence and employ new approaches to model parameterization and to modeling itself. Such things as knowledge bases, case-based and rule-based decision making and multi-objective decision making techniques along with the more familiar mathematical models, graphic user interfaces and GIS systems could all be quite useful in this area. The ARS needs to examine the systems approach to defining problems and then design, build and implement solutions based on a variety of technologies.

Conclusion

This report addresses some of the key research issues related to spatial and temporal variability. Because it is a central issue in the physical sciences, it is of great interest to many different disciplines. Great effort has gone, and will continue to go, into research on this topic. Progress has been made. However, critical research gaps still exist. Some of these gaps were identified in this report:

1) our inability to control or quantify errors associated with measurement techniques;

2) a failure to incorporate spatial variability into models and their estimates;

3) the need to establishing better methods for extrapolating between the scale at which parameters were evaluated and the scale at which they are applied; and,

4) a lack of good methods for characterizing spatial variability.

These scientific gaps create research opportunities. Some of these opportunities were identified in this report:

1) relating hydraulic properties to vegetation type and other methods of indirect parameter estimation;

2) evaluating the significance of temporal variability in hydrologic processes;

3) expanding applications of remote sensing;

4) improving methods for analyzing large data sets; and,

5) planning more integrated research projects.

We must understand spatial variability in order to develop appropriate theory in hydrologic models. Efforts to elucidate the complications which form the gap between what is found in the field and what our simplified mathematical models are capable of representing must forge ahead.

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Remote Sensing Applications to Hydrology

W.P. Kustas[1], M.S. Moran[2], K.S. Humes[1], and C.C. Truman[3]

Summary

There are several attributes to remote sensing technology that make it a unique resource for hydrology. It provides areal information as opposed to point data so that spatially distributed quantities can be mapped over large areas. Furthermore, remote sensing data have been related to geophysical quantities that are strongly linked to hydrologic processes (Engman and Gurney 1991). From satellites, information is available at regional and global scales allowing for a time series of images over the area of interest. This allows for the monitoring of both short-term and long-term changes in our environment. Applications include vegetation assessment, snow-ice mapping, surface-water delineation and monitoring of anthropogenic impacts such as urbanization.

However, the application of remote sensing to hydrology is still in its infancy. Several important issues still have to be resolved before this technology can be applied operationally. One important issue is the interpretation of remote sensing data. In other words, how easily can we discern what surface and atmospheric properties significantly affect the observations. A related issue is how to most effectively utilize information contained in different wavelengths of the electromagnetic spectrum to describe the hydrologic state of the system. Finally, a third issue is once we are able to interpret the remote sensing data and obtain estimates of system states, how this spatial and temporal information can be utilized in hydrologic models.

Introduction

For hydrology, remote sensing has mainly been used to provide system states of the surface. These include soil moisture, surface temperature, vegetation cover, land use, snow cover, and sediment load and turbidity of water bodies. Determination of surface fluxes and atmospheric quantities in the lower atmosphere usually requires ancillary data and some type of modeling approach. However, there are some exceptions where remotely-sensed data are used exclusively to determine a flux or system state. These include incoming solar radiation from weather satellites (Pinker and Laszlo 1990), precipitation and wind fields with the new ground-based radar systems, NEXRAD (Klazura and Imy 1993), and wind speed and turbulent fluxes with doppler Lidar (Gal-Chen et al. 1992).

At present, the remotely sensed products used most frequently for hydrologic applications have come from weather satellites with sensors in the optical wavebands (i.e., visible to thermal-infrared wavelengths). For details concerning theory and applications of optical remote sensing see Asrar

[1] Hydrologists, USDA-ARS, Building 007, Room 104, BARC-West, Beltsville, MD 20705.
[2] Physical Scientist, USDA-ARS, 4331 East Broadway Road, Phoenix, AZ 85040.
[3] Soil Scientist, USDA-ARS, P. O. Box 946, Tifton, GA 31793.

(1989). The potential of utilizing satellites with microwave sensors has only been recently investigated and appears to provide additional information useful for hydrologic applications (Choudhury 1991).

Of the system states mentioned above, surface temperature, T_s, is probably the parameter most closely connected to the condition or state of the surface. The temporal and spatial variation in T_s is affected by the amount and type of vegetation cover, amount of snow cover, soil moisture and meteorological conditions (viz., radiation, wind speed, air temperature and relative humidity). As a result energy balance models using remote sensing data have surface temperature as their primary boundary condition. For a review of modeling approaches see Jackson (1985), Carlson (1986), and Schmugge and Becker (1991). Most operational models are either statistical or analytical solutions to the energy balance equation. Simplifications usually required for operational models result in the computation of daily fluxes. In many cases, daily output of evapotranspiration (ET) is relevant for irrigation scheduling and most other hydrologic applications where daily to monthly water balance estimates of basins is the primary goal. More complex models compute the components of the surface energy balance over a diurnal cycle and use remote sensing data to initialize and update the model. These are more suitable for areas with rapidly changing environmental conditions and where remote sensing data is not readily available. However, many of these models require ancillary meteorological measurements which in many instances will not be located in the area of interest. Therefore attempts have been made to couple an atmospheric boundary layer model that simulates regional atmospheric conditions given initial large-scale meteorological information with the land surface (Carlson et al. 1981). This would eliminate the dependence on continuous in-situ meteorological measurements.

Vegetation cover, biomass and leaf area index have been correlated with vegetation indices computed from visible and near-infrared reflectance data. The most commonly used index is the Normalized Difference Vegetation Index (NDVI). Global maps of NDVI have been generated using NOAA AVHRR satellites (Ohring et al. 1989). However, it is important to note that the relationship between vegetation cover and vegetation indices is not unique and will depend upon the surface being considered. Since weather satellites can provide both T_s and NDVI maps, approaches have been developed for utilizing the T_s-NDVI relationship to estimate model parameters and to compute fluxes in heterogeneous regions (Carlson et al. 1990, Price 1990, Nemani et al. 1993). Again, it needs to be emphasized that the T_s-NDVI relationship is empirical and hence cannot be transferred to other climates and land surfaces.

Closely related to surface temperature is soil moisture. Soil moisture describes the hydrological state of the surface because it influences the rate of infiltration and ET (Engman and Gurney 1991). These variables in turn, influence runoff and local climate. Remote sensing in the microwave wavelengths offers the most promise for mapping soil moisture. Existing satellites with passive microwave sensors show a potential for mapping soil moisture in arid regions with sparse vegetation cover (e.g., Owe et al. 1992). But they are not very useful in most other areas due to the attenuation of the signal by vegetation cover (Hemysfield and Fulton 1992). Use of a L-band sensor would allow soil moisture observations over a much broader range of cover conditions since it is least affected by vegetation and surface roughness conditions (Jackson, 1993). The pixel resolution of a L-band instrument from space would be too course for any basin scale observations, but technological improvements in sensor design are being made to improve the resolution. Active microwave sensors do not suffer from resolution problems; however, backscatter signals are significantly affected by soil roughness, topography and vegetation. Algorithms have been developed to account for these effects in theory, but need field validation (Engman 1991).

The microwave measurements described above penetrate the first few centimeters of the soil surface. Therefore, they provide no subsurface information on soil moisture or soil properties. Ground penetrating radar (GPR) has been used as a nondestructive and cost-efficient way of mapping subsurface soils, water tables, lake bottoms and storage conditions. Current applications include describing mechanisms and processes controlling water and agrichemical movement in Coastal Plain soils (Truman et al. 1993).

Unfortunately, most hydrologic models are not designed to utilize spatially distributed maps of soil moisture and soil hydraulic properties. An experimental investigation by Engman et al. (1989) showed that a time series of soil moisture maps collected from an aircraft-based sensor could be used to simulate the water balance of a small basin. Other possible uses for repetitive soil moisture mapping over a basin is to update and calibrate model parameters and correct errors resulting from point measurements of other hydrologic parameters, such as rainfall (Jackson et al. 1981).

Hydrologic models have been adapted to use land use classifications derived from remote sensing satellites for runoff predictions (Jackson et al. 1976). Also there have been early attempts at developing a hydrologic model designed to use remote sensing input data and a geographic information system (GIS) as a data management tool (Groves and Ragan 1983).

Recent studies suggest incorporating remote sensing into hydrologic models can improve model performance. Ottlé et al. (1989) modified a hydrological model to simulate the hydrologic and energy budget at the soil surface for a 100 x 100 km^2 area in France. Surface temperature observations from NOAA satellite images were used to obtain water deficit maps for the region and were compared to simulated water contents. They concluded that remote sensing data could reinitialize the water budget model estimate of soil moisture to correct for errors in input parameters such as precipitation, which is probably the least reliable input at regional scales. They also observed that remote sensing observations alone cannot evaluate vegetation stress, and that atmospheric forcing (i.e., air temperature, wind speed and vapor pressure deficit) must be considered. Duchon et al. (1992) adapted SWRRB (Simulator for Water Resources in Rural Basins) developed by ARS to use Landsat and GOES data in modeling the water budget for the Little Washita Watershed. The Landsat data permitted them to divide the basin into homogeneous subareas instead of standard subbasins with heterogeneous land cover. The GOES data provided daily insolation for the model. A sensitivity analysis of the model suggested that a temperature bias of a few degrees can have a significant impact on the growing season and monthly water and energy budgets for winter wheat.

Optical remote sensing of the areal distribution of snow cover in mountainous basins has been used for the snowmelt-runoff model (SRM). SRM is an operational model which makes use of the percentage area of the basin or elevation zone covered by snow as a primary input. Further developments with this model are summarized in Rango (1993). Also, Rango (1993) provides an overview of the potential of microwave remote sensing for determining snowpack information such as snow depth, water equivalent and presence of liquid water. This information would greatly improve the modeling of the timing and amount of snowbelt runoff.

Optical remote sensing is also used in water quality studies. Observations have shown that the presence of sediment in water changes the reflectance characteristics of water dramatically (e.g., Ritchie et al. 1976). However, the relationships are empirical and therefore vary with environmental conditions. On the other hand, a spatial distribution of sediment over a large water body is only feasible from satellite-based measurements.

The above is a brief overview of possible applications of remote sensing to hydrology. The issues discussed in this paper reflect areas needing further investigation in order that the potential of remote sensing can be fully realized. The issues are

a) Interpretation of Remote Sensing Data - The process of converting remotely sensed reflected and emitted electromagnetic radiation into hydrologic variables.

b) Utilization of Remotely Sensed Data in Models - How to develop new or modify existing hydrologic models to take advantage of the spatial and temporal information from remote sensing.

c) Synergism of Different Data Types - What information is contained in different wavelengths of the electromagnetic spectrum to improve estimates of system states and fluxes.

For each issue, the scientific challenges and research opportunities are presented.

Scientific Challenges

Interpretation of Remote Sensing Data

In order to incorporate remotely sensed data into most hydrologic models, spectral measurements should ideally be sensitive to surface characteristics and invariant with non-surface properties such as sun/sensor viewing geometry, atmosphere and sensor calibration. The influence of the latter three factors on sensor signal and methods for accounting for them will be addressed.

Sun/Sensor Geometry

Several satellites support sensors that are pointable to over $\pm 30°$ from nadir along a plane perpendicular to their near-polar orbits. This feature allows frequent coverage of a specified site but it also leads to complications in image interpretation associated with off-nadir measurements. First, the oblique viewing angle results in a longer atmospheric path length and a more complex surface interaction that must be considered in atmospheric correction. Second, results from previous research have shown that there is a substantial variation in detected surface radiance with increasing off-nadir viewing angle. Jackson et al. (1990) measured bidirectional reflectance factors (BRFs) of bare soil and full-cover wheat and found that off-nadir measurements of BRF could differ from nadir measurements by up to 400% in the visible bands, and that the magnitude of the difference was dependent upon surface roughness, spectral wavelength and solar zenith angle. In an analysis of multiple SPOT HRV images, Qi et al. (1993) concluded that influences of atmosphere, view and soil background on vegetation indices and reflectances were intricately coupled and dependent on surface characteristics. They could not find one single component that consistently dominated the variations encountered.

Based on these findings, the hopes for an empirical or simple trigonometric correction algorithm (such as a cosine correction) appear dim. However, there are a number of Bidirectional Reflectance Distribution Function (BRDF) simulation models that could potentially provide a solution to this problem. To date, few studies have dealt with the comparison of these models and the definition of a strategy to use them with satellite data. This should be the direction of future research and development.

Atmosphere
The interaction of electromagnetic radiation with the earth's atmosphere is complex. In this section, discussion will be limited to simple interactions within the atmospheric windows of the visible, near-IR and thermal-IR spectrum.

Visible and near-IR energy. In the visible and near-IR spectrum, the influence of atmosphere on sensor signal results in scattering of energy for shorter wavelengths (blue) and absorption of energy for the longer wavelengths (near-IR). Thus, surface reflectances derived from satellite data are commonly overestimated in the blue spectrum and underestimated in the near-IR. The influences of scattering and absorption are generally offset for the intermediate wavelengths, resulting in relatively smaller atmospheric effects in the green and red spectrum.

Consequently, the magnitude of atmospheric effects on sensor signal depends on both the atmospheric conditions (optical depth and water vapor content) and the spectral wavelength. Even for clear, dry atmospheric conditions, Pinter et al. (1990) reported that atmospheric variations had a large influence on the spectral vegetation index derived from SPOT HRV images. In fact, for a spectral band-ratioed vegetation index, they found that the influence of atmosphere was greater than that of viewing angle variation. The most promising method for atmospheric correction is the use of multiple-scattering radiative transfer codes (RTC) to characterize the scattering and absorption properties of the atmosphere. Moran et al. (1992) found that use of such RTCs with reasonable estimates of atmospheric visibility and water vapor content significantly improved estimates of surface reflectance in all visible and near-IR wavelengths. Several user-friendly RTCs are currently available and some are even being incorporated into turnkey image-processing packages such as ERDAS.

The importance of using a multiple-scattering RTC for retrieval of surface reflectance and radiance from satellite DC should be emphasized here. Because of the complexity of the interaction of energy and the atmosphere, some simple image-based corrections can lead to greater error than no correction at all.

Thermal energy. Atmospheric absorption and scattering of thermal-IR radiation can cause serious errors in the evaluation of surface temperature from satellite-based sensors. Li and McDonnell (1988) reported that 10-60% of the radiation emitted from the ocean was absorbed by atmospheric water vapor before it reached satellite altitude. Thus, the sea surface temperature detected by the satellite appeared to be 1-10 °K lower than that at the sea surface, due almost entirely to water vapor absorption. As precipitable water increases, ground temperatures detected by satellite sensors tend to converge; consequently, the overall effect of the atmosphere is to reduce the thermal image contrast.

The atmospheric correction of satellite-based thermal data has principally involved simple regression of surface temperature and satellite digital data, regressive multi-band techniques, empirical multi-altitude correction techniques, and atmospheric correction models. For single-band thermal sensors (such as Landsat TM), the only feasible correction options are either empirical linear regression with surface temperatures or use of atmospheric radiative transfer codes. The former requires knowledge of surface temperatures and emissivities of a cool and warm site during the overpass, and the latter requires some knowledge of the atmosphere, acquired with radiosonde instrumentation.

It is possible to acquire radiosonde data from weather stations throughout the United States, but these data will not necessarily be coincident in time or space with the satellite image. Wukelic et al.

(1989) found that, when local, coincident radiosonde data were used with the Lowtran RTC to adjust for atmospheric effects, the satellite-derived temperatures were within 1°C of ground temperature values. However, using non-local and non-coincident radiosonde data resulted in errors as large as 12°C. Moran (1990) confirmed these results for an independent data set acquired in Arizona.

The direction for future research in this area will likely include further investigation of the incorporation of non-local, non-coincident radiosonde information in RTCs. Considering the inherent difficulty of such an approach, there is a great need for creative alternatives to the use of radiosonde measurements for atmospheric correction of thermal data. An expert's workshop designed to assess the current state and future direction for use of remotely-sensed thermal data is scheduled for November 1993.

Sensor Calibration

Satellite sensors that measure reflected and emitted energy from the earth's surface degrade with time and thus require periodic post-launch calibration if quantitative data are desired. A knowledge of the absolute calibration of airborne sensors is necessary to distinguish between temporal changes in surface radiance and changes in the sensor's response due to degradation with time.

Theoretically, there is an exponential degradation of sensor performance in the early life of the sensor and then the calibration should become more stable. The magnitude of the initial degradation and the stability of the subsequent calibration vary with each sensor. For example, in a summary of in-flight calibrations of the SPOT HRV sensor, Gellman et al. (1993) found that there was an exponential degradation of sensor performance during the first 100 days after launch, but that the calibration appeared stable over the following few years. However, in a similar summary of Landsat-5 TM calibrations, Thome et al. (1993) found that there were significant reductions in responsivity several years after launch. These results documented the differential reduction in responsivity of orbiting sensors over time, and emphasized the need for frequent, in-flight calibrations for all satellite-based sensors.

Relations Between Remote Sensing Data and Surface Properties

There is ample evidence that remotely sensed spectral data can provide useful information regarding such surface properties as LAI, plant biomass, percent vegetation cover, soil moisture, percent snow cover and water sediment/chlorophyll content. However, the majority of work has been directed toward empirical relations between spectral data and surface properties. This has resulted in relations that are often site-, time-, and surface-specific, and can't be applied to other geographic locations, vegetation types, or to times other than those for which the relation was derived. In response to these limitations, current research has taken three basic directions. In one approach, similar data sets acquired under diverse conditions are combined to derive "universal" empirical relations between spectral data and the desired surface property. Since many environmental and measurement factors can affect these empirical relationships, this approach may not yield very reliable information.

A more promising approach is to combine physically-based models with remote sensing data and some ancillary information (meteorological, edaphic or agronomic) to derive surface information. The synergy of models, limited site information and measurements of surface spectral characteristics holds the most potential for providing reliable estimates of surface hydrologic properties. This modeling/remote sensing approach combines the accuracy of the remotely-sensed estimates with the

temporal frequency of a simulation model, and avoids the extensive site information required by more complex simulation models.

A third approach has emerged in recent years with the launch of new multi-spectral sensors that provide information in the visible, near- and mid-IR, thermal and microwave spectrum at similar spatial and temporal resolutions. The combination of multispectral data into a single relation with surface properties often circumvents the limitations of a single spectral wavelength. For example, radar backscatter is often associated with soil moisture conditions but this relation is confounded by variations in vegetation density. Some vegetation indices derived from visible and near-IR reflectance are sensitive to vegetation characteristics and yet insensitive to soil moisture. Thus, there is potential to combine radar data with shortwave reflectance to improve estimates of soil moisture.

Utilization of Remotely Sensed Data in Hydrologic Models

Most hydrologic models were designed and calibrated with point data. Therefore, the spatial and temporal information from remote sensing are not easily employed and usually requires considerable time and effort in order to adapt the models to use this information. Some exceptions were noted in the Introduction.

In studies by Duchon et al. (1992) and Ottlé et al. (1989), it was important to obtain atmospheric parameters at basin scales. This points to one of the critical scaling problems that is still unresolved, namely how to extrapolate atmospheric parameters measured in one location to other areas with different landcover and environmental conditions. Ground-based meteorological data will only be indicative of local environmental conditions. To date no operational method for interpolating between measurement sites is based on surface-atmosphere dynamics. The inability to link atmospheric and land-surface processes within the framework of a hydrologic model is a major shortcoming and is one of the major unsolved problems in the hydrological sciences (National Research Council 1991, Engman 1993).

Another related issue is determining area-averaged soil hydraulic parameters. One approach is to have land use and soils information mapped for the region. These are used to define the parameters for "homogeneous" subareas (Duchon et al. 1992, Sucksdorff and Ottlé 1990). An alternative approach is to treat the heterogeneous surface as a homogeneous system defined by a set of "effective" hydraulic properties that need to be determined. The physical meaning of these "effective" parameters and their application to large-scale hydrology are still being explored (Beven, 1989). To determine these effective parameters, Feddes et al. (1993) investigated the feasibility of using remotely sensed soil moisture and surface temperature for computing the surface energy and water balance. The energy and water balance calculated for each pixel is the boundary condition required to extract the effective soil hydraulic parameters used by the hydrologic model. Consequently, no a priori knowledge of scaling locally determined parameters is required.

Remote sensing appears to be the only technology available for scaling land-surface processes and variables. At this time, techniques to perform such scaling are either conceptual or if algorithms exist, they do not appear easily verified with traditional ground measurements. Remote sensing may be a very useful tool for validating the scaling techniques. But, as discussed here, the interpretation of the remote sensing data is not trivial and is in itself a challenging area of research.

Synergism of Data Types
The use of specific remote sensing data types for hydrologic applications were discussed in the Introduction section. Visible and near-infrared reflectance data are the data types most frequently used to quantify vegetation and snow cover. A combination of data in the visible, near-infrared and thermal wavebands have been shown to be useful in estimating components of the surface energy balance. Passive microwave data are effective in estimating values of spatially distributed near-surface soil moisture. The use of a time series of microwave and thermal data in combination with a model of soil heat and moisture flux has shown some potential for the quantitative inference of soil hydraulic characteristics.

To be sure, there are still scientific challenges to be addressed in the use of these data types individually. However, the state of the art in the application of each of the data types has matured to the degree that the strengths, limitations and uncertainties involved in each data type are relatively well known. A considerable amount of research is now being devoted to exploring the feasibility of synergistic use of these data types in combination. Justification for this effort comes from the observation that the primary signal for some data types is a source of noise for other data types. By using the data types in combination, not only does one gain information about different surface features, but also the potential to derive certain characteristics with greater certainty (as the sources of "noise" for individual data types are quantified with other data types).

The Fundamental Questions
The primary challenge that we now face is to determine how to best use these different data types in combination for the applications outlined above. The first step is to determine how to utilize the information content of the multiple data types. This must be done in different contexts for different applications, such as:

a) Direct calculation of surface parameters or fluxes from a combination of data types (e.g., instantaneous surface energy balance components; surface roughness parameters)

b) Use of the various data types for setting initial conditions and updating state variables in soil/vegetation/atmosphere transfer models (e.g., deriving soil hydraulic properties or other controlling parameters from a temporal series of different data types)

Since most hydrologic models were designed to utilize point-based data instead of the areally-integrated data at various spatial scales, the next most crucial challenge in utilizing combined data types is to ascertain the model complexity required at different spatial scales of observation and conversely, the spatial resolution of various data types required for the use in these models.

Some additional considerations which must necessarily be addressed include:

a) Different spatial and temporal scales of measurements for different data types

b) Different times of acquisition for satellite-based data

Research Opportunities

Interpretation of Remote Sensing Data
Over the past ten years, research emphasis has shifted from plot-scale research with ground-based sensors to field- and regional-scale research with aircraft and satellite sensors. This shift not only

results in new research objectives, such as analysis of atmospheric and sensor view-angle effects, but also new experimental approaches. Field experiments are necessarily more temporally intensive and spatially extensive. Such intensive field experiments are generally characterized by the convergence of many scientists at a single site for an extended period to acquire meteorological, agronomic, and atmospheric data coincident with several aircraft and satellite overpasses. The data sets generated from these experiments have been crucial for preliminary assessment of the utility of remotely sensed data for resource monitoring and management. The common goal of these field/modeling studies is generally twofold: 1) validation of various algorithms for correcting remotely sensed data for atmosphere, view/solar angle and sensor calibration; and 2) hydrologic model verification, calibration, and incorporation with remotely sensed inputs. Such experiments, planned for different ecosystems throughout the world, provide hydrologic research opportunities at a wide variety of spatial scales.

Utilization of Remotely Sensed Data in Hydrologic Models
A review by Renard (1993) documents the development by ARS of 11 hydrologic models for watershed and engineering applications. The models were mainly calibrated with point and plot information and/or watershed outflow measurements. To apply these models to a basin, land use and soil survey maps have either been used to lump a number of hydrologic processes into one parameter (i.e., SCS curve number) or used to define areas with similar hydrologic characteristics in order to assign values to the model parameters used in simulating the process.
The real opportunity with remote sensing lies in the potential to provide system states (e.g., soil moisture, surface temperature and surface cover information) over space and time. This information can initialize and update model simulations. Therefore a major effort should be made to investigate the feasibility of adapting these models to use this spatial information.

Model calculations of the hydrologic fluxes need verification both at local and basin scales. This requires large scale interdisciplinary field experiments where the model parameters and fluxes can be measured. Indeed, further progress in the development of land-surface parameterizations linking hydrologic and atmospheric processes requires data collected at larger scales than those customary in the past (Dozier 1990).

As a first step, validation of model output will require comparison with the water balance of basins of various sizes. ARS maintains over 30 experimental watersheds in the continental U.S. ranging in size from 0.2 ha to 637 km^2. They cover most climatic regions of the country and are well instrumented. The rainfall/runoff data are organized and distributed by the Water Data Center in Beltsville, MD (Thurman and Roberts 1993). Their value and interests as sites for investigating the application of remote sensing to large scale hydrology is evident from the recent field experiments conducted in the Walnut Gulch Watershed (MONSOON '90), in the Mahantango Watershed (MAC-Hydro-90) and in the Little Washita Watershed (Washita '92).

Synergism of Data Types
One of the primary factors limiting this type of research in the past has been the availability of high quality, near-simultaneous data sets of both optical and microwave data at the watershed scale. Several multi-disciplinary field experiments (for which ARS personnel have had a major role in planning and/or participation) have been carried out in recent years which provide the unique opportunity to study the combined use of data types over a variety of surfaces and climatic regimes. These include the following experiments:

- MONSOON '90 (2 week intensive period with good range of moisture conditions; TIMS/NS001 and PBMR data acquired 5 to 6 times)

- Walnut Gulch '92 (March-> October monitoring of entire growing season; TM data acquired whenever weather conditions were appropriate; near-simultaneous ERS-1 radar data on several occasions)

- Washita '92 (2 week intensive period with good range of moisture conditions; TIMS/NS001 and ESTAR data acquired a number of times)

- HAPEX-Sahel (4 week intensive aircraft campaign in context of seasonal monitoring; TM/SPOT, TIMS/NS001, PBMR and ERS-1 data)

As we gain insight from the combined analyses of data from these experiments, we can know better how to plan and utilize data from future field experiments at increasing spatial scales. These include: the SALSA (Southern Arizona Land Surface Atmosphere) Experiment; further investigations over the Little Washita Watershed and surroundings; the large-scale GEWEX (Global Energy and Water Experiment) initiative.

Two other important points to keep in mind as we work towards these goals are as follows:

(1) It is likely that future experiments of this sort will involve NASA aircraft and instruments; however, given the high cost of data acquisition from the NASA aircraft, budget constraints, and the increasing pool of users requesting aircraft time, it is realistic to expect that time with the NASA aircraft will be quite limited and will place significant constraints on the timing and duration of future field experiments. In past field studies we were able to use the services of an ARS remote sensing aircraft facility (Weslaco Aerocommander). Several of the instruments used to acquire the remotely sensed data types described above have each been individually flown in the Aerocommander. As we determine the optimal use of the combined data types, we should think in terms of a multi-instrument package (eg., Tom Jackson's microwave radiome-ter, vis/nir/thermal sensors and a laser profiler) which could be flown on the Aerocommander and could be shared by several groups. The instruments in this type of aircraft would most likely provide transect data rather than image data. It should be thought of not as a substitute for the type of experiments which can be carried out with the NASA aircraft, but rather as a way to augment those with data from a more flexible platform which could be used for experiments of different scope and magnitude, and much more under our control than those which involve the NASA aircraft.

(2) Spatially-distributed modeling of storm and interstorm processes is required in order to take full advantage of combined data types. We should keep in mind that in addition to our involvement in distributed modeling through our own research and interactions with the academic community, a tremendous amount of expertise and interest in this topic exists within the research branches of operational agencies such as the NWS and USGS and in the effort by TERRA.

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Watershed Characterization and Fractals

J.D. Garbrecht[1], J.G. Arnold[2], and M.S. Seyfried[3]

Summary

The role of Geographic Information Systems (GIS) in watershed characterization, the characterization of spatial variability, and the potential of the theory of fractal geometry in watershed characterization are reviewed to identify scientific challenges and research opportunities that may lead to new and improved methods and technologies for solving our water resources problems. GIS relies heavily on visualization approaches to characterize distributed watershed features and adds a new dimension to the traditional characterization by abstract mathematical and statistical formulations. It is a powerful tool that can lead to new insights and state-of-the-art methodologies to address problems regarding spatial variability and watershed discretization and parameterization. With regard to the quantification of spatial variability, spatial variability is generally only meaningful in association with a specific hydrologic process and scale of observation. Research opportunities include the determination of the interdependence between spatial variability, scale, hydrologic processes, and temporal and spatial resolution of these processes, as well as the development of a classification for spatial variability. Regarding the theory of fractal geometry, it provides a new mathematical framework to quantify scale dependent heterogeneities. Its strong points appear to be in the scaling of self-similar heterogeneities, in providing conceptual models for self-similar structures, and in directing and focusing the search for similarities or thresholds over a range of scales. The descriptive capabilities of fractal geometry with respect to the characterization of structures remains to be tested.

Introduction

Watershed characterization refers to the determination of distinguishing attributes, features or characteristics of a watershed. Watershed characteristics can related to topographic features, drainage network geometry and topology, land use, vegetation cover, soil properties, and so forth. They can be used to identify a particular watershed, differentiate between watersheds, or help in the description and interpretation of watershed processes. Watershed characterization is not to be confused with watershed parameterization which refers to the quantification of watershed characteristics. It should also not be confused with watershed discretization which refers to the subdivision of a watershed into discreet components. Both, watershed parameterization and discretization, are generally a result of watershed characterization.

Watershed characterization is generally not a goal in itself. It is usually a necessary step for ulterior usage such as for hydrologic, geologic, or geomorphic investigations. Therefore, the specific

[1] Research Hydraulic Engineer, USDA-ARS, P. O. Box 1430, Durant, OK 74702.
[2] Agricultural Engineer, USDA-ARS, 808 East Blackland Road, Temple, TX 76502.
[3] Research Hydraulic Engineer, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.

approach used in watershed characterization often depends on its subsequent use. This was recognized early on by Horton (1932) who pointed out that relevant watershed characteristics are those that are most general in nature and that have a pronounced correlation with the subject matter under consideration. If hydrology is the subject under consideration, then watershed characterization may include such factors as watershed area, shape, compactness, ruggedness, relief, slope, drainage density, soil properties, vegetation cover, etc. These factors have often been used in regression studies that established relationships between the watershed characteristics and the water and sediment runoff of the watershed (Patton and Baker 1976, Potter 1953). The drainage network is an important watershed characteristic that has generated intense research and many publications on topics such as the generation of random walk networks, network evolution, and network scaling properties. Other work has focused on directly relating watershed and network attributes to runoff characteristics.

With the computer revolution in the sixties and seventies, distributed modeling became popular and watershed characterization took a new turn towards watershed discretization. This approach focused on determining the characteristics of subcomponents of a watershed with the understanding that the additional detail will lead to a better representation of the overall watershed and to a better interpretation of the processes and system controlling the watershed response. Many large, detailed, complex, and data intensive distributed models evolved and reemphasized the issue of spatial variability and data availability. The quantification of spatial variability has since remained a problem and an important research topic.

Over the last 10 years major breakthroughs in computer hardware and software capabilities have been achieved. Also digitized and remotely sensed data are becoming increasingly available. These developments have lead to new computer tools one of which is the Geographic Information System (GIS). GIS is nowadays a common and often necessary tools in hydrologic and other investigations involving spatial data. With this tool new watershed characterization approaches are inevitable and one can expect that these will help in the issue of reduction and interpretation of the ever increasing volume of spatial data. In addition to these advances in computing capabilities and data availability, new theories, such as the theory of chaos and fractal geometry, have emerged and are being applied to a wide range of practical problems. In particular the theory of fractal geometry has been cited as a fresh approach to the issues of scaling, representation of variability at different scales, and structuring to what appears chaotic (Burrough 1983, Tyler and Wheatcraft 1990b, Tyler and Wheatcraft 1992). These theoretical and technological advances open new avenues for our research and data analysis, and also for watershed characterization.

The main objective of this paper is to identify and present scientific challenges and research opportunities in the area of watershed characterization that will lead to new and improved methods and technologies for solving our water resources problems. Three aspects relating to watershed characterization are selected for indepth treatment in this paper:

- the role and potential of GIS in watershed characterization;
- the characterization of spatial variability; and,
- the application of the theory of fractal geometry in watershed characterization.

Special emphasis is placed on the third topic dealing with the potential use of the theory of fractal geometry in the context of watershed characterization. An introduction to each of the above topics is given in the following.

GIS and Watershed Characterization

GISs have become an important tool for watershed characterization. One early application of GIS to watershed characterization was for simple screening for potential problems and index mapping. One of the best known examples of this is the US-EPA application of the DRASTIC index (Aller 1985). DRASTIC consists of a weighted numerical scheme that considers depth to groundwater, net recharge rate, the aquifer media, soil characteristics, topography, impact of the vadose zone, and hydraulic conductivity of the aquifer. By comparison of the characteristics weighted to form the DRASTIC vulnerability index, the relative likelihood that groundwater will become contaminated if a waste source is placed on the surface at one point in the region as compared to another. This type of characterization is well suited to GIS implementation and uses empirical relations that do not contain any explicit physical laws.

GISs are a powerful tool for watershed discretization. A GIS can easily subdivide a large basin into smaller subbasins. The three most common discretization schemes are grids, TINs, and subwatersheds.

- Grids: Grids are developed in GIS by creating a rectangular mesh of points and joining them with lines, thus partitioning the domain into a rectangular pattern of subareas. Grid structures are the basis of analysis in raster GIS systems, and are a good way of characterizing the topography and any type of continuously distributed data of the land surface in vector GIS systems (Maidment 1993). The gridded land surface data is called a Digital Elevation Model.

- TINs: A triangulated irregular network is a triangular mesh drawn on a scattered set of points. A TIN requires only a small percentage of the number of points that a DEM needs to represent the surface terrain with equal accuracy because the points can be placed strategically on the surface (Jones et al. 1990). The triangular mesh is also used in hydrology since it is the basis for finite element solution of flow and transport problems. The linkage between the TIN data structure in GIS and the triangular mesh in finite element algorithms is one way finite element codes could be linked to GIS (Moore et al. 1993). TINs have also been used for watershed and stream network delineation (Jones et al. 1990) and some automated routines have been developed called TIN cascading, by which a first approximation to surface water velocity and erosion rates can be derived from a TIN model of the land surface.

- Subwatersheds: One of the most common methods to discretize a watershed is by subwatersheds. Maidment (1993) describes the linked-lumped system in which a watershed is divided into subwatersheds that are each characterized as lumped systems which are connected by stream links. This representation is routinely employed in surface water hydrology. Considerable research has been devoted to developing the hydrologic features of surface terrain using DEMs. The most widely utilized procedure is based on the "four-point" model (Jenson and Domingue 1988, Jenson 1991, Martz and Garbrecht 1992, Garbrecht and Martz 1993) in which water from each grid cell flows onto the lowest of the eight adjacent grid squares. By tracking the simulated water from cell to cell, a set of "hypothetical" flow paths is traced and a set of subwatershed boundaries can be delineated from those cells that do not receive water from adjacent cells. The stream network is determined from the set of cells receiving water

from a specified number of other cells. This approach is useful for the study and characterization of large scale rural watersheds but is limited in urban areas (Maidment 1993).

Once a watershed has been discretized, GIS can be utilized to estimate subwatershed characteristics that include soils, land use, land cover, and topographic properties. Satellite data (Landsat-TM, SPOT-HRV, and NOAA-AVHRR) are common sources of land use and land cover information required for watershed characterization. Characterization is usually not an end in itself, and in hydrology is commonly related to parameterization of hydrologic models. In many GIS/model applications there is an implicit assumption that the grid cells or TINs can be considered homogeneous in terms of hydrologic characteristics. However, it is obvious for many scales of investigation that this is not practical (Moore et al. 1993). In most GIS applications to the linked-lumped subwatershed system, GIS have been used to estimate subwatershed characteristics by selecting dominant soils and land use in a subwatershed. GIS are also used to define topographic characteristics within a subwatershed such as average land slopes and channel slopes and lengths (Srinivasan and Arnold 1993, Sasowsky and Gardner 1991).

Characterization of Spatial Variability

Spatial variability became an important topic of study in hydrology as the development of computer technology progressed to the point that watersheds could be discretized and physically-based approaches to hydrologic simulation could be employed. These physically-based hydrologic models have great potential for solving societal problems and aiding in water management because they provide a rationale for extrapolation of hydrologic knowledge from one location to other, ungaged locations, or to future, unmeasured conditions. The rationale is that, because the same physical laws apply throughout the environment, a model based on physical principles should also have a broad application. This is important because many of the questions being asked concern impacts of current actions on future conditions. Other, empirically-based models, account for spatial variability but require calibration data which may not exist.

At this point it is a little too early to say if the physically-based modeling approach will live up to its potential. For one thing, this approach has been developed relatively recently, with perhaps the earliest example in 1974 (Stephenson and Freeze 1974). In addition, there are new developments and databases being constantly under development. Results to date, however, have been mixed at best. Use of uncalibrated data sets in physically-based models often results in substantial deviations from observed reality (Andersson 1992, Beven 1989, Grayson et al. 1992).

At this point it is impossible to say whether the difficulties arise from a failure to properly apply physical and biological principles (i.e., are we using the right equations?) or to an inability to parameterize models with sufficient accuracy. On the one hand, the physically-based equations used have been validated under small-scale controlled laboratory or plot conditions. It is not clear how parameters such as soil-water potential apply to the much larger scales required for hydrologic modeling. On the other hand, if one assumes that the equations are appropriate, the high degree of spatial and temporal variability exhibited by critical watershed properties makes parameterization problematic.

These two issues of scale and variability are interrelated and central to the problem of watershed characterization. They are also considered to be central to hydrology (Dooge 1982). An increase in scale has at least two effects on variability. One is that other values of the property of interest are introduced. These may be thought of as additional realizations in a stationary field. Thus, while a 0.1 m^2 plot may be considered to be homogeneous with respect to relevant soil and surface

characteristics, an increase in the scale of interest to include a several hectare field, for example, would undoubtedly introduce similar but different values. If the landscape property in question has a major impact on hydrologic response, it may be necessary to include that variability as part of the characterization. Hydrologic response from a randomly variable area may be considerably different from that of a homogeneous one (Freeze 1980, Smith and Hebbert 1979).

The other effect is that additional sources of variability are introduced and stationarity is lost. Changes in soil parent material, slopes or vegetation may result in dramatically different kinds of hydrologic behavior which may control the response for the area of interest. It is often the case, for example, that a small part of the watershed may contribute most of the storm runoff (Amerman and McGuinness 1967, Betson and Marius 1969, Dunne and Black 1970). The location of this small part may have a large effect on the functioning on the watershed. In those cases it is essential that the actual spatial distribution of the property be accounted for (Smith and Hebbert 1979).

Whether or not a watershed characteristic is part of a random, stationary field depends on the scale of interest. The slope configuration of a small watershed, for example, may control the hydrologic response at that scale. At a larger scale, slopes may be considered some kind of random distribution.

For purposes of this discussion we consider three characterizations of spatial variability: (i), homogeneous, where there is no spatial variability, (ii) deterministic, where the actual spatial distribution of critical variables is known, and (iii), stochastic, where the variability is considered to be random. These characterizations are consistent with others (Phillip 1980, Rao and Wagenet 1985). It is generally recognized in the spatial variability literature that parameter values are composed of deterministic and random components (Webster and Oliver 1990). It is also recognized that variability characterized as random may be composed of smaller-scale deterministic variability. Characterization for hydrologic modeling is different from spatial variability per se in that the impact of the variability of a property on the hydrologic response of interest, is important. Variability of many different landscape properties may have no impact on hydrologic response and may therefore be ignored. Other factors may be critical and therefore require precise treatment.

There are some examples of models and/or modeling approaches that attempt to address these issues. Two examples are TOPMODEL (Beven and Kirkby 1979) and the variable source area model (Troendle 1985). In TOPMODEL important topographic effects that may control runoff are accounted for while in the variable source area model rapid storm flow response is explained by the portion of the watershed subject to saturated overland flow. In both cases the important controlling processes are felt to result from deterministic variability that is explicitly modeled at the expense of detailed, small scale process representation throughout the watershed. These approaches have been labeled "quasi-physical" because they simplify processes. However, given the nature of spatial variability, they may actually better represent hydrologic processes than more traditional physically-based models.

Another, more general approach, which is consistent with the nature of variability described above, is the representative elementary area (REA) concept (Wood et al. 1990). The idea is that statistical properties, such as the mean and variance or correlation length can adequately describe hydrologic response at scales larger than the REA. At scales smaller than the REA actual patterns of rainfall, topography, soil, etc., must be explicitly considered. In other words, at scales greater than the REA variability may be considered to be stochastic while at smaller scales it must be considered to be

deterministic. Wood et al. (1990) present evidence from simulations that there is, indeed, an REA for watersheds.

Fractal Geometry and Watershed Characterization

Introduction. In traditional Euclidean geometry, points, lines, surfaces and volumes serve as the basis to describe the geometry of nature. For example, given a measuring unit of length E, the length of any straight line can easily be measured.

$$L = N * E = \text{constant} \tag{1}$$

where N is the number of measuring units E needed to cover the straight line. If the size of E is halved, N will increase by a factor of 2, which is consistent with the notion that the straight line has a constant, finite length. The same can be said for a surface and a volume. However, most natural objects are highly irregular in shape over a wide range of scales and are not easily described within the Euclidean system. A classical example is the outline of a coast (Richardson 1961). Viewed from an earth orbiting satellite, the coastline appears to be composed of large scale irregularities such as deltas, gulfs, and/or estuaries. From an aircraft forty-thousand feet above ground, additional details, such as bays, inlets and/or peninsulas become noticeable. Then, from a bird's eye view, further details such as sub-bays, coves and small inlets become apparent. Even closer, from a beach walker's perspective, details, such as sand bars and local protuberances, become visible. And, if the beach walker were to crawl along the coastline, the crawler would see the detailed outline produced by rocks and pebbles. This repeating irregularity at consecutively smaller scales poses a problem in the determination of the length of the coastline because, as the scale of the coastline increases, additional details become apparent and the length that follows these details necessarily increases. The product N * E in Eq. 1 is no longer a constant (Mandelbrot 1983). The length is said to be scale dependent. The traditional notion of Euclidean length in this case is meaningless without specifying the scale at which the length measurement was made. The question arises as to which length is the correct length, or which scale must be used to obtain the correct length, or if there is a way of expressing a length measurement that is scale independent.

Another example that defies description within the Euclidean system is the surface of clouds. Large cumulus clouds consist of big heaps that have bulges which in turn have smaller bumps with bumps on them, and so forth.

Irregular objects such as the coastline and clouds, are called fractal objects. Mathematically speaking, an object with an ever perpetuating irregular boundary has an infinite length or surface, and no defined tangent at any point. It is a non-differentiable boundary because every attempt to split it up into smaller parts results in the resolution of still more structure or detail. This is unacceptable in Euclidean geometry. The problem is not a trivial one and has frustrated mathematicians for a long time. Fractals have also practical implications. For example, we know that the length of the common border between two countries must be one and the same value. Yet, the lengths of the common border between Spain and Portugal, or Belgium and The Netherlands, as reported by these countries encyclopedias, differ by up to 20% (Richardson 1961). The discrepancy is partly due to differences in map scale of each country. Mandelbrot (1983) showed that it suffices that the scale differs by a factor of 2 to produce the above discrepancy, and it should not come as a surprise that a small country (represented by larger scale maps) measures its borders more accurately than its bigger neighbor (represented by smaller scale maps). One can therefore expect practical engineering measurements of natural objects from maps of different scale to produce apparent inconsistencies.

There are many other objects in nature that display fractal behavior over many scales but within physically meaningful limits. For example trees, blood vessels, lungs and drainage networks display an repeating finer branching pattern with increasing scale; landscapes and cloud surfaces display a repeating finer surface texture with increasing scale. Irregular patterns in time such as turbulence, water levels in reservoirs, and Brownian motion also display fractal behaviors. Other examples include patterns in price changes, errors in data transmission, word frequencies in written text, aggregates of particles, pore structure of porous media, etc.

The theory of fractal geometry provides us with a mathematical framework for the understanding and quantification of such irregular and seemingly complex objects that appear to display similar patterns over a range of scales. Fractal geometry views the object on a multitude of scales, each having its levels of detail and intricacy. It allows us to relate the measurements to the scale, to quantify the degree of object irregularity, and to scale the irregularities across a wide range of scales. As a result, many complex natural systems, such as coastlines, drainage networks, clouds and porous media, may be quantified by applying fractal concepts to describe their apparent heterogeneity. The following are a few important definitions of fractal terms used in the subsequent discussion of the theory of fractal geometry.

Fractals. Mandelbrot (1983) offers the following definition of a fractal. This mathematical definition is given here only for information purposes. The simplified definition by Feder (1988) that is given thereafter is sufficient to understand the concepts of fractal geometry for discussion in this paper.

> *"A fractal is by definition a set for which the Hausdorff-Besicovitch dimension strictly exceeds the topological dimension."*

In this definition the topological dimension can be understood as the integer dimension in the Euclidean system, and the Hausdorff-Besicovitch dimension D of a set S is the critical dimension for which the measure M_d changes from zero to infinity.

$$M_d = \sum \gamma(d)\,\delta^d = \gamma(d)\,N(\delta)\,\delta^d \;\; \underset{\delta \to 0}{LIM} \to \begin{Bmatrix} 0, & d > D; \\ \infty, & d < D. \end{Bmatrix} \qquad (2)$$

where M_d is the d-measure of the set, γ is a geometrical factor, N is the number of unit measurements of size δ needed to cover the object, and δ is the unit measurement size.

A simplified definition of fractals has been given in Feder (1988):

> *"A fractal is a shape made of parts similar to the whole in some way."*

and,

> *"A fractal looks the same whatever scale."*

Therefore, irregular objects that consist of shapes and patterns (length, surface, volume, or features of higher dimension) that repeat themselves in some way at different scales are called fractal objects. The term "fractal" has been introduced by Mandelbrot and is derived from the Latin "fractus" (meaning "fractional", "uneven"). It is intended to designate objects with highly indented, rough shapes, and which have a non integer dimension. An example of a line having fractal

behavior is shown in Figure 1b. The irregularities (in a statistical sense) at each scale cannot be distinguished one from another. On the other hand, irregular objects that do not have similar or related patterns at various scales are not fractals. Similarity of some kind is a fundamental property of fractal geometry (Wheatcraft and Tyler 1988). Irregular objects that can ultimately be represented by a series of small straight lines, plane surfaces, or small cubes are called rectifiable objects. They have a finite length, surface or volume. Most natural objects have a lower limit to fractal behavior and are rectifiable at some scale. An example of a rectifiable line is shown in Figure 1a.

Pure fractal objects. Pure fractal objects are irregular objects with an ever perpetuating patterns over all scales. Every attempt to focus onto a smaller part results in the resolution of still more detail (Burrough 1981). Pure fractal objects are generally the realm of mathematics or abstract constructs. The Koch curve in Figure 2 is a pure fractal because finer and finer patterns are recursively generated ad infinitum. Most natural objects are not pure fractals because the concept ever perpetuating irregularity breaks down at a very small scale (molecular or atomic scale) and at the very large scale (planetary scale). They are objects with fractal behavior within a specified range of scales. When working with natural fractal objects the lower and upper bounds must be specified.

Fractal dimension. The mathematical definition of a fractal dimension is given by Eq. 2. A practical way to determining the fractal dimension is illustrated by use of an example adapted from Hjelmfelt (1988). In this example the goal is the length determination of a river reach. Given a map of small scale and a unit of length measurement of 5 mm, one can walk the measuring unit along the trace of the river and determine the length of the river as:

$$L_s = N_s * E_s \tag{3}$$

where L is the total river length, N is the number of unit length measurements needed to cover the trace of the river, E is the distance represented by the unit length measurement on the map, and the subscript s indicates small scale. To get a more accurate length, one could use a map of moderate scale that gives additional detail. Using subscript m to indicate medium scale and the same unit length measurement, the length of the river is given as:

$$L_m = N_m * E_m \tag{4}$$

An even better length can be found using a large scale map and again the same unit length measurement. This time the subscript b refers to large scale:

$$L_b = N_b * E_b \tag{5}$$

The measured river length is unlikely to be the same for each measurement. One expects that:

$$L_s < L_m < L_b \tag{6}$$

because as more detailed maps are used, more irregularities can be followed by the unit length measurement. A log-log plot of total length, L, versus distance E gives a straight line as shown in Figure 3 (Hjelmfelt 1988), or

$$\log(L) = \log(K) + (1 - D) * \log(E) \tag{7}$$

$\underline{L(E) = K * E^{(1-D)}}$ (8)

where log(K) is the intercept and (1 - D) is the slope of the line. The expression for the slope arises from the notation that is used in fractal geometry. D is termed the "fractal dimension", E is often called the scale of observation or the "ruler length", and K is a constant (Mandelbrot 1983).

$K = N * E^D = \text{constant}$ (9)

Several important observations are in place regarding Eq. 8. First, it shows that the relation between the measured variable L and the scale E is a power law. Second, it shows that river lengths are scale-dependent if their fractal dimension is other than unity. When the fractal dimension equals unity, the lengths are scale independent and traditional Euclidean concepts apply. When the fractal dimension exceeds unity, river length measurements grow as the ruler length E decreases. In more general terms the findings imply that measurements of irregular objects from maps, such as coastline, watershed boundaries, streams and contours, are likely to be map-scale dependent and exhibit fractal behavior. Third, given the fractal dimension of an object and its measurement at one scale, the corresponding measurement at any other scale can be determined (provided the fractal dimension does not change with scale). This has important implications for scaling observed heterogeneities. Fourth, the value of the fractal dimension D of a curve is a measure of the degree of irregularity or twisting of the curve. The larger D, the wilder the twisting of the curve. A fractal dimension of 2 implies that the curve is twisting so badly that it fills the entire plane (Wheatcraft and Tyler 1988). An example of a curve having different fractal dimensions is shown in Figure 4. The fractal dimension of a line or a curve is always between 1 and 2. For surfaces and volumes (not treated in the above example) the fractal dimension ranges from 2 to 3 and from 3 to 4, respectively.

Self-similar. Self-similarity of a fractal set refers to the property of small parts of an object to resemble larger parts. Self-similar objects with irregular patterns that look alike at the various scales are said to be scale-invariant. Self-similarity can be exact or statistical. Exact self-similarity means that smaller features are exactly a scaled down version of larger ones. The Koch curve shown in Figure 2 displays exact self-similarity. Statistical self-similarity means that the statistics of the features at the different scales are similar. For example the lines in Figure 1b are said to be statistically self-similar. For an object to be self-similar it must display isotropic scaling properties, i.e. the scaling of the patterns is direction independent (or the scaling is the same in all of the objects dimensions). As a rule, for natural objects, self-similarity manifests itself only in the statistical sense (Nikora 1991).

Self-affine. The analysis of the fractal structure of records in time emphasizes the need to distinguish between self-affine and self-similar fractals. Self-affine fractal sets are sets that scale differently in two or more dimensions. For example, in time series the ordinate and the time axis (abscissa) may scale differently. Simple geometric figures may also be self-affine. For example, a circle which scales differently along two of its principle axis yields an ellipse. A circle and an ellipse are self-affine. Similarly, the rectangles with diagonals in Figure 5 are self-affine (Le Mehaute 1991). Self-affine fractal sets have anisotropic scaling properties, they scale differently in each of the objects dimensions.

Multi-fractal. Many natural objects display a certain degree of statistical self-similarity over many spatial scales, yet there are others that have their levels of variability clustered at particular scales of distinct dimensions connected by transition zones. This behavior does not exclude them from the

fractal concept (Mandelbrot 1977) and are referred to as multi-fractal objects. The fractal dimension would be useful for separating scales of variation that might be the result of particular natural processes.

Scaling with fractals. One of the primary characteristics of fractals is that they look similar in some way over a range of scales. This property leads to the concept of fractal scaling. Fractal scaling provides us with transformation rules in which an object or process is mapped onto itself and describes how things look at a different scale. The fractal dimension characterizes the scaling properties of the object, and it provides a similarity exponent because it tells how the associated measure changes after a change of scale (La Barbera and Rosso 1989). It is important to recognize that traditional (linear) scaling cannot be applied to objects that exhibit fractal scaling (Tyler and Wheatcraft 1990a). For example, referring to Eq. 8, the length measurement at any scale (ruler length) can be predicted if the length and fractal dimension at another scale is known. Linear scaling would not have been successful.

Evaluation of the theory of fractal geometry. It was Benoit Mandelbrot who in the 1970's introduced the theory of fractal geometry. He recognized that for most natural objects the amount of resolvable detail is a function of scale. As the scale is increased, more and more previously unresolved features appear (See Appendix I for an introduction to fractal structures and for definitions of terms). Mandelbrot (1983) introduced the term fractal specifically for temporal or spatial geometric structures that are continuous but non-differentiable, and that exhibit partial correlation over many scales. Non-differentiable continuous structures cannot be described in the Euclidean system. Every attempt to rectify such a structure by splitting it up into smaller parts results in the resolution of still more detail on these smaller parts. The theory of fractal geometry provides us with a mathematical framework for the understanding and quantification of such irregular and seemingly complex structures that display similar patterns or features over a range of scales.

The increasing number of publications in geophysical sciences that relate to the theory of fractal geometry does not only indicate a wide-spread interest in the subject, but also its potential wide range of applicability. Fractal concepts are used to describe network structures, landscape texture, irregular boundaries of all kinds, flow paths in porous media, aggregates and clusters, time series, soil chemistry, ecologic models, parameter estimation, ecosystem structure, molecular structures, and so forth. These numerous applications suggest that a large number of natural objects, structures, or phenomena display some degree of fractal behavior. Examining even a small sample of recent publications on fractals is beyond the intent and scope of this paper. In the following a few general observations on the theory of fractal geometry are made to assist in the discussion of opportunities and challenges regarding the application of fractal concepts in watershed characterization. These observation are those of the authors as well as those of a few scientists that have shared their opinions with the authors. As such, the observations are not to be considered as a final and universal judgement on the theory of fractal geometry, but as a biased opinion of a very few.

From a practical stand point, the fractal dimension of a structure can be obtained by plotting a log-log plot of a property of interest versus a measure of scale. If the data plots as a straight line, the property exhibits fractal behavior and the slope of the line is the fractal dimension of the property. Back-transformed into linear scale, the straight line yields a power law equation. This approach to data analysis is commonly referred to as data fitting and has been around for many decades. Data fitting, when it is unsupported by theoretical or physical arguments, has often been viewed as a

superficial and casual approach in scientific analysis. The practical steps in the analysis of the fractal behavior of natural objects is quite similar to traditional data fitting. However, the theory of fractal geometry has contributed significantly by: (1) focusing data analyses on scale dependent behavior; (2) providing a rational for log-log data fitting; and, (3) anchoring the observed fractal behavior in a strong mathematical and physical foundation.

Given this new mathematical and scientific framework, it can now be expected, as it is already apparent in the literature, that a large number of past geophysical problems relating to scale will be revisited from the view point of fractal geometry. This will lead to new insights and interesting theories. Undoubtedly, previously irrelevant topics may suddenly become (or appear) relevant once they are recast in fractal terms.

Several comments are made on the practical aspect of identifying fractal behavior. First, a log-log transformation often de-sensitizes data patterns and results in a data plot that appears to follow a straight line, especially when the range on the scale axis is rather narrow (less than two orders of magnitude). This may lead to the belief that a given phenomenon, process or structure has a constant fractal dimension, whereas a larger range of application may show that the fractal dimension itself is in some way a function of scale. Ideally, the data should cover several orders of magnitude before constant fractal behavior can be claimed with a certain degree of confidence. For example, Mesa and Gupta (1987) imply that the average fractal dimension of river networks varies with basin size, and Rosso et al. (1991) suggest a multifractal approach to analyze the geometry of complex river network systems (Rosso et al. 1991).

Second, the values for fractal dimension have a small range. The fractal dimension of an irregular line is between 1 and 2, and that of an irregular surface between 2 and 3. This narrow range of values makes the fractal dimension a somewhat insensitive parameter as illustrated for river length data. The fractal dimension of eight rivers in Missouri was reported to vary between 1.036 and 1.291 with a mean value of 1.158 (Hjelmfelt 1988). The fractal dimension of seven rivers of Moldavia was reported to vary between 1.08 and 1.25 with a mean value of 1.151 (Nikora 1991). And, the fractal dimension of 10 interior river segments on the Eaton River were reported to vary between 1.035 and 1.127 with a mean of 1.085 (Robert and Roy 1990). Mandelbrot (1983) hypothesized that the value for rivers should be close to 1.136. Since the values of fractal dimension of river length for rivers in different geographic locations appear to be relatively close together (in the above examples between 1.09 and 1.16), the fractal dimension is more a characteristic of rivers in general, than a characteristic to distinguish river types. This has two implications: (1) fractals appear to be more useful for scaling than for discriminating between river types, and (2) if the fractal dimensions of most rivers are similar, then their scaling properties must also be similar, i.e. every river scales the same way. Similar insensitivities are apparent for shoreline lengths of Swedish lakes (Goodchild 1980), and coastline and border lengths (Mandelbrot 1983).

Third, the fractal dimensions of geographic objects that are inferred from maps may be biased, because the degree of irregularity of the objects is not only dependent on scale, but also on the mapping standards and generalization. These may change from one scale to another, or from one map type to another. For example, Robert and Roy (1990) report that the scale dependency of stream length is not only related to the increase in stream complexity, but also to the headwater extension of the stream network as the map scale becomes larger.

Given the above restrictions, some scientists believe that the application of fractal geometry to geophysical forms, processes or phenomena will result in a new geomorphic, topologic or statistical parameter (the fractal dimension) that could be used for scaling, but that it will not lead to significant advances in the understanding of the workings of the physical processes and the way in which they shape our environment. They view fractal geometry as a descriptive tool with limited potential for physical interpretation or predictive applications. They feel that the application of the theory to real world problems has not proven itself, that the significance and longterm impact of the theory has not been established, and that the theory is not more useful than traditional methods (for example statistics). They suggest that fractal geometry should undergo rigorous scrutiny to determine its true value in an environment where stochastic differences are the norm. For example, Liu (1992) states that although some progress has been made in estimating fractal dimension of stream networks, the fractal structure and properties of stream networks as a disordered system remain poorly understood. And, the treatment of a problem using fractal theory may not be consistent with traditional methods and that it may introduce new problems in the formulation of balance and governing equations based on average values of intrinsic properties (Tyler and Wheatcraft 1990a).

Other scientists, who have worked extensively with fractals, feel that the theory has proven itself and point out that fractal mathematics and fractal scaling have been successfully applied to a wide range of geophysical problems, ranging from simple descriptions to the development of physically consistent theories. For example, fractal scaling provides innovative approaches in relating self-similar subsurface heterogeneities at different scales and in modeling such an environment. The use of fractal scaling to describe nested structures within structures and the use of the Sierpinski carpet as a conceptual model of pore structures appear to have been quite successful (Tyler and Wheatcraft 1990a). Others have reported success in the description of surface roughness and texture using the fractal approach. In general, these scientists focus on the strong aspects of fractal geometry. They point out that fractals are particularly well suited to help find scales at which change occurs (change in fractal dimension). Since different processes often produce different fractal dimensions, the change in fractal dimension can help identify a change in dominant processes and the scale at which it occurs. Also, in contrast to the previously stated limitations of fractals to discriminate between types of similar structures (rivers), fractals are said to be strong in identifying similarities between different structures.

Scientific Challenges

GIS and Watershed Characterization

Although GIS's are an extremely powerful tool in watershed characterization and discretization, their ultimate contribution to hydrology may be as a tool for studying the impact of spatial variability and spatial lumping schemes. GIS will not answer the research questions that need to be answered but should be viewed as a tool to perform the research much more rapidly. The challenge is to establish distributed watershed characterization and discretization methodologies that are primarily based on visualization approaches as opposed to more traditional abstract mathematical and statistical formulations.

Characterization of Spatial Variability

To characterize critical or impacting spatial variability of watershed components in such a way that hydrologic processes of interest are quantitatively simulated.

Fractal Geometry and Watershed Characterization

The previous review of the theory of fractal geometry shows that the theory has limitations in its practical applications, but that it also has strong points that open new avenues to bring order to the apparent complex disorder of nature. The theory complements current approaches in scaling and parameterization problems. Its strongest points appear to be in the scaling of self-similar heterogeneities, in providing conceptual models for self-similar structures, and in directing and focusing research to areas of similarities or to locations of discontinuities. Its descriptive and predictive capabilities with respect to the characterization of structures remains to be established. Overall, there is no doubt that the theory of fractal geometry represents a great opportunity, a fresh approach to investigate scale related problems, and a stimulus for novel thoughts and new ideas. The challenge is to identify watershed characteristics that exhibit fractal behavior and to establish the usefulness of the fractal property as a practical watershed characteristic, a scaling property, or a conceptual model for the characteristic under consideration.

Research Opportunities

GIS and Watershed Characterization

Discretization schemes. GIS can be used as a tool to aid in determining the hydrologic response of the various discretization schemes such as the grid cell, TINs, and subwatersheds. GIS can also speed the analysis to determine to what extent watersheds should be partitioned to simulate their hydrologic characteristics with acceptable accuracy. In other words, can general rules be developed regarding discretization approach and subarea sizes?

Subwatershed lumping schemes. Assuming dominant soils and land use properties to characterize a lumped subwatershed can lead to significant errors when applied to hydrologic models (Arnold 1992). What kind of lumping schemes to characterize subwatersheds are acceptable for representing hydrologic processes?

Watershed heterogeneity. There is potential for GIS to assist in better understanding watershed heterogeneity. GIS could be used to develop parameters of watershed heterogeneity that would be useful not only in watershed characterization but also as a guide for modeling of watershed processes. Again, watershed characteristics that would be important indicators of heterogeneity would be soil, land use, and topographic properties.

Characterization of Spatial Variability

1. How can a conceptual framework for describing spatial variability be designed? Perhaps the REA approach as outlined above or some extension of the characterization we presented is such a framework, although much testing is required.

2. What procedures should be used to characterize spatial variability at different scales? That is, when is it appropriate to use homogenous descriptions and when are stochastic or deterministic ones required? Field experimentation will be required, but the difficulty of such experiments will probably require that they be carried out in conjunction with simulations. This approach has been explored for establishing the REA. The difficulty is that just describing variability is not enough. The hydrologic impact of that variability must also be established.

3. Are there physical laws or generalizations that can be applied across different watersheds? Experimental data will be available for only limited areas but the demand will be for many. Some means of generalizing characterizations, perhaps in terms of watershed size, climate or other property, will be extremely important.

4. How can a hybridized modeling approach be incorporated? Stochastic and deterministic approaches are generally presented as contrasting approaches but large scale models must somehow incorporate both. At the subgrid level, for instance, homogeneity is generally assumed even though substantial variability is present. To overcome this statistical parameters or possibly scaling approaches may be used.

5. How can the interrelationships between temporal and spatial variability be addressed? This paper has dealt exclusively with spatial variability independent of temporal concerns, but this is not the actual case. If it is reasonable that variability may be considered to be stochastic when it is sufficiently "sampled" by having a large area of interest, then it is also reasonable to consider that increasing the time scale of interest will have a qualitatively similar effect. This implies that the characterization of spatial variability is dependent on the temporal as well and spatial scale of interest.

6. How can measurement scale be made compatible with the simulation scale? Characterization and measurement are inextricably linked. A characterization remains theory until measurements are made while measurements are only numbers until they are employed to characterize the object of interest. There has been a recent explosion of measurement technology, particularly in remote sensing, which may be especially useful for large scale characterization.

Fractal Geometry and Watershed Characterization

1. Determine the fractal structure of the watershed landscape, drainage network and spatial heterogeneity (spatial variability).

2. Establish the fractal property as a meaningful parameter to identify similarities or differences between watersheds.

3. Investigate the use of fractal structures as a conceptual model for spatial heterogeneities (spatial variability).

4. Research the scaling properties of fractal watershed characteristics and potential to scale small watershed characteristics up to infer the properties of corresponding large watershed characteristics.

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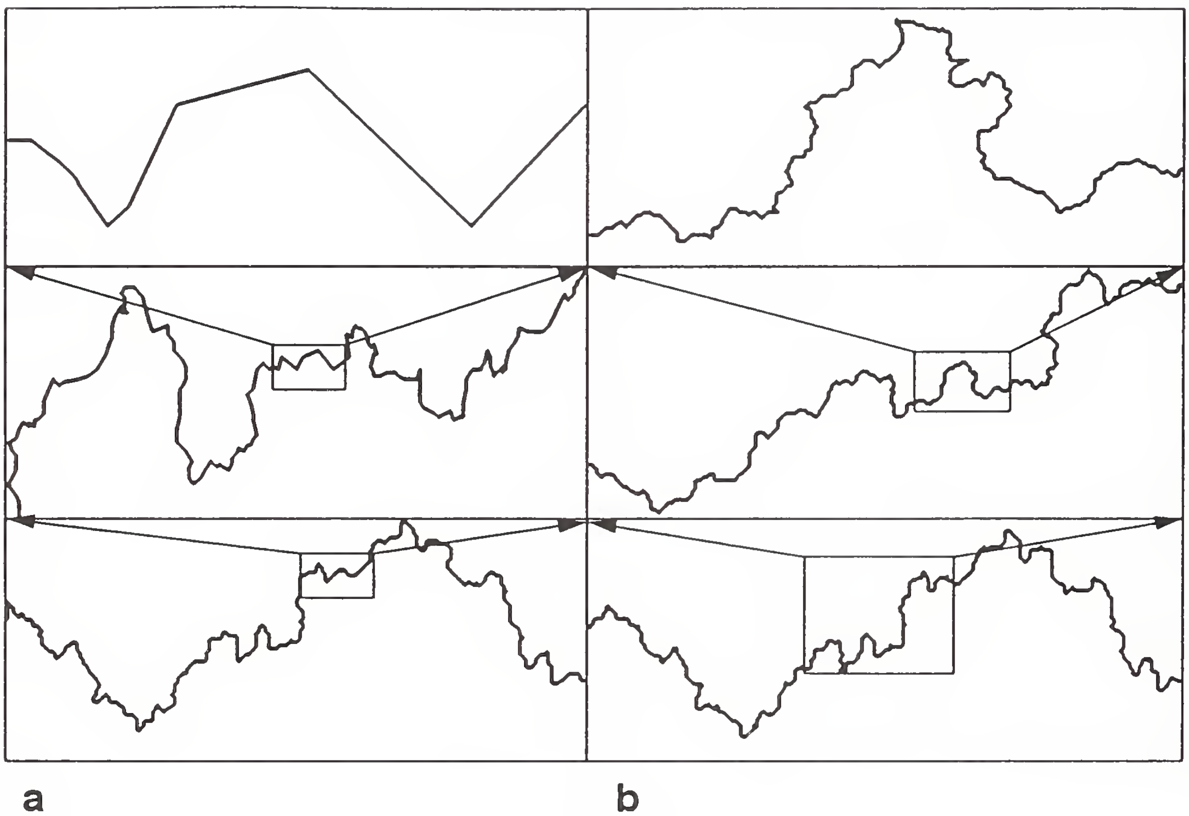

Figure 1. a) Nonfractal scaling/ b) fractal scaling (after Tyler and Wheatcraft, 1990; reproduced with permission of author).

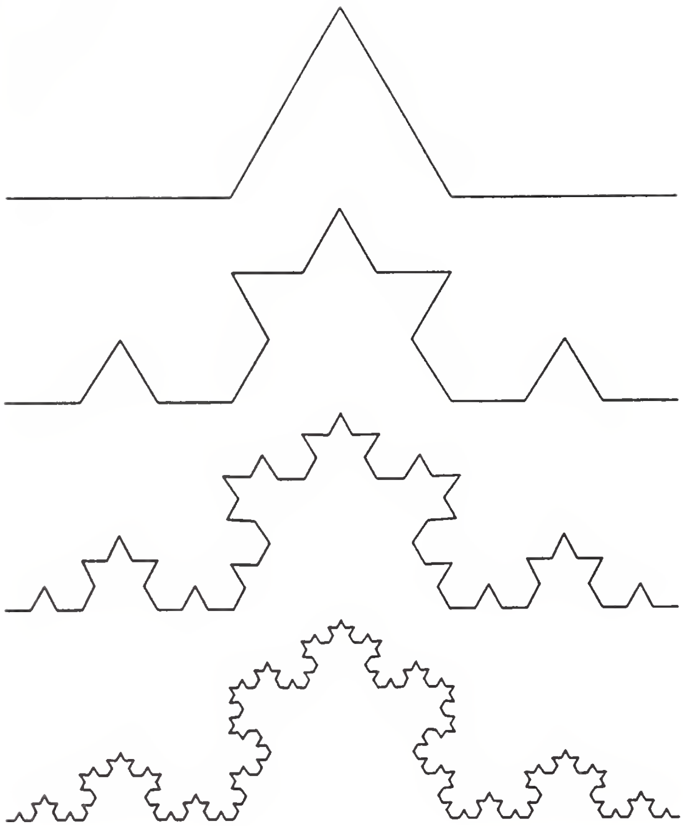

Figure 2. The Koch curve carried to four levels of recursion. Further recursions are obtained by replacing every straight line by a scaled down version of the first line. This can mathematically be carried ad infinitum to yield a curve with infinite length and no tangent at any point.

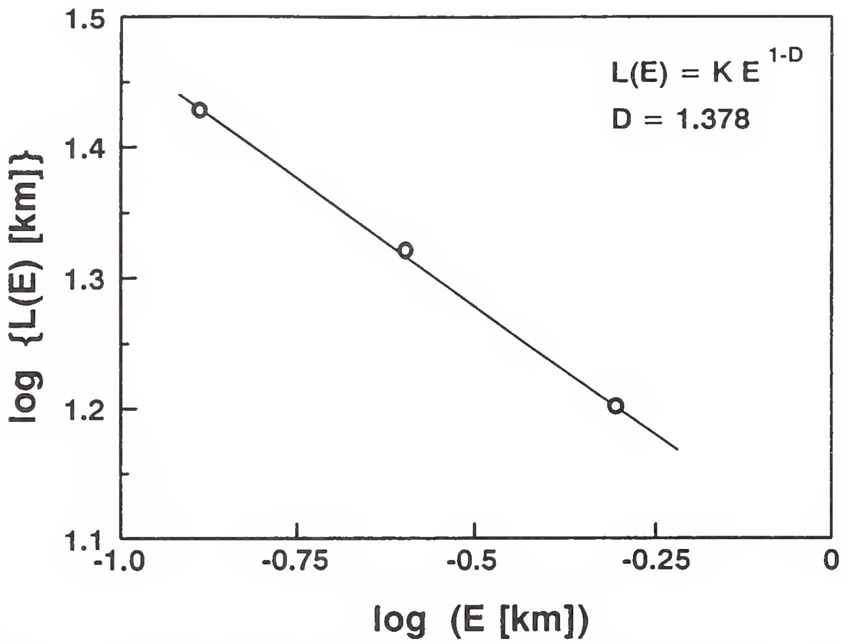

Figure 3. Influence of map scale on measured length; the values given in the figure are only illustrative.

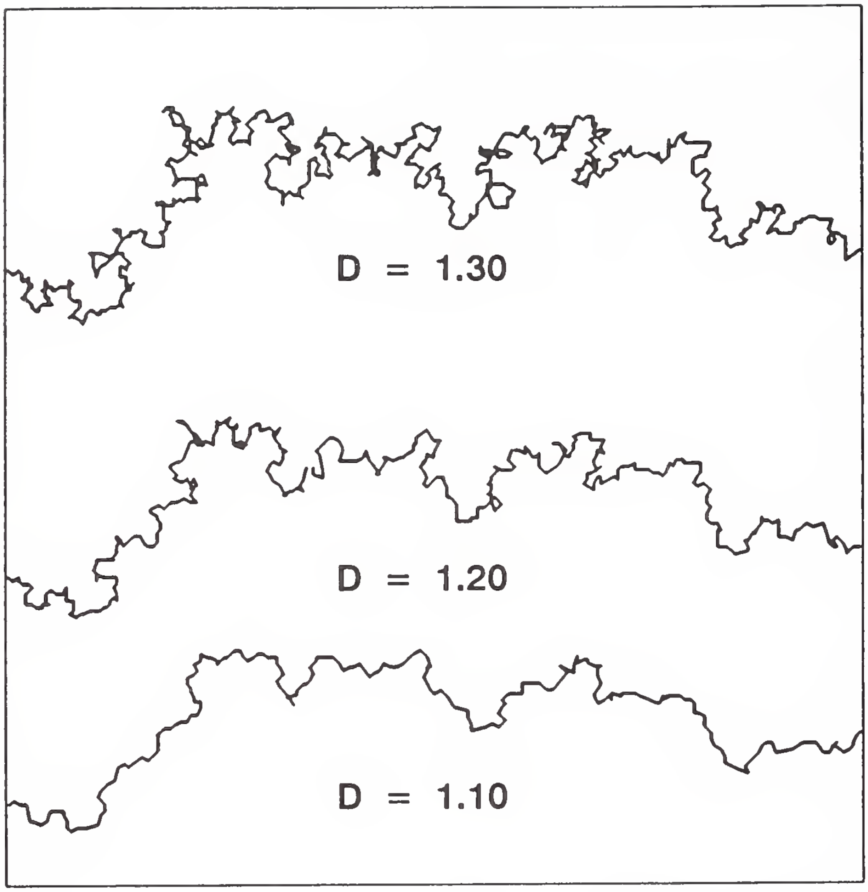

Figure 4. The effect of varying the fractal dimension for a stochastic fractal trace (after Wheatcraft and Tyler, 1988; reproduced with permission of the author).

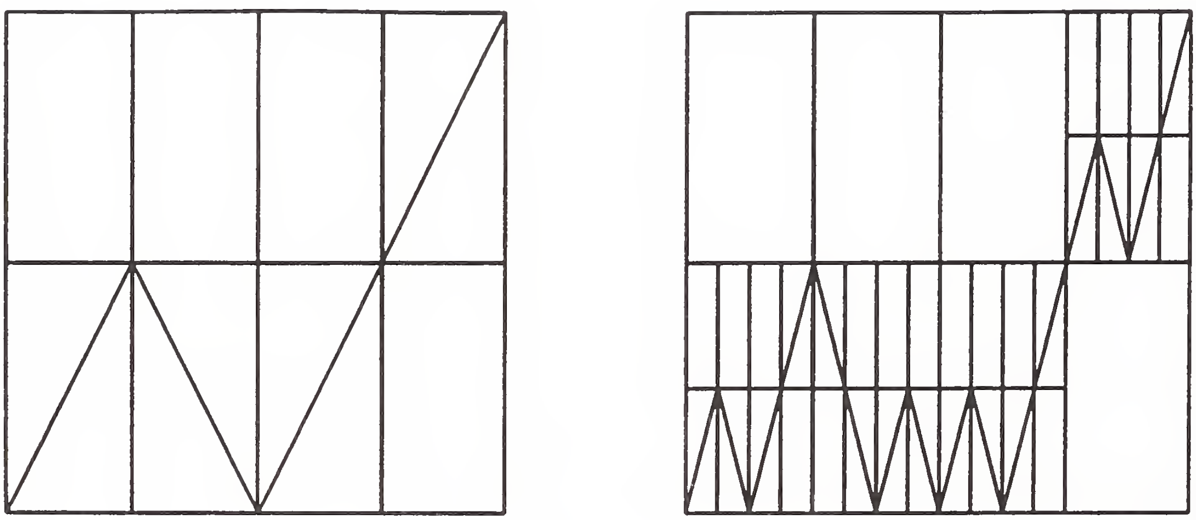

Figure 5. Example of a self-affine set. The rectangles with diagonals are all scaled similarly.

Chaos Theory in Hydrology

G.N. Flerchinger[1], M.S. Moran[2], F.B. Pierson[3], and G. Fernandez[4]

Summary

Many aspects of hydrology are complex and respond in an apparently random manner, eluding our efforts to accurately predict their outcome or occurrence. Yet, it can be argued that there is order underlying all hydrologic processes since they are ultimately controlled by laws of nature, i.e. the laws of physics, chemistry and thermodynamics. To help make sense out the apparent randomness and complexity, a number of hydrologists are turning toward chaos to help determine if there is a simple set of underlying laws or equations controlling the behavior of certain hydrologic processes.

Chaos, a strange type of mathematical order that gives the illusion of being random, has proved valuable in a number of fields to explain how complex behavior can arise from relatively simple equations. Fields where chaos has been applied successfully include chemistry, physics, medicine, population biology and meteorology. Researchers have used chaos to explain the strange behavior of systems varying from complicated rhythms of the human heart to the unpredictable tumbling of Hyperion, a potato-shaped moon of Saturn (Gleick 1987, Stewart 1989).

In many ways chaos is a misnomer. Chaos implies a lack of order, or behavior without pattern. Chaos theory, however, deals with the search of order hidden within apparently random, unpredictable behavior (Wilcox et al. 1991). Thus, in its application to hydrology, scientists hope to discover a deterministic element in what has been assumed to be stochastic.

This paper gives an overview of the application of chaos in hydrology. It is our intention to briefly review some areas of hydrology where chaos theory has been applied and to discuss some of the limitations and opportunities associated with chaos. Because most hydrologist have, at best, limited exposure to chaos theory, we start by introducing some simple concepts for understanding chaos.

Introduction

Although most people can relate to chaos in their everyday lives, few have an understanding of it in a mathematic or scientific sense. A mathematical definition for chaos is a deterministic system which produces apparently random or stochastic behavior (Stewart 1989). Thus, chaos is deterministic -- it obeys mathematical equations! Normally, anything that obeys mathematical equations (such as a the projectile of a ball subject to gravity, the conduction of heat through an object, or movement of planets within the solar system) behaves quite regularly and is quite

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[1] Research Hydraulic Engineer, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[2] Research Physical Scientist, USDA-ARS, 2000 East Allen Road, Tucson, AZ 85719.
[3] Hydrologist, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[4] Hydrologist, USDA-ARS, P. O. Box 1430, Durant, OK 74702.

predictable. Chaos is different, exhibiting quite irregular and unpredictable behavior, yet always following the physical laws governing the system. In many instances, a system can exhibit very regular and predictable behavior under a given set of conditions, and be quite chaotic under slightly different conditions.

Chaotic systems in many cases are not complicated, but rather complex (Procaccia 1988). Chaos can often be characterized by complex behavior arising from very simple, albeit non-linear dynamic equations. This behavior is so complex, so sensitive to measurement, that it appears random. A defining characteristic of chaotic behavior is its sensitivity to initial conditions, meaning that small perturbations of initial conditions have large future consequences. This in turn implies that the long-term behavior of a chaotic system is not predictable because we can seldom measure initial conditions accurately enough. A related property of chaotic systems is loss of information about initial conditions.

Chaotic behavior can arise from surprisingly simple non-linear differential equations. These type of equations arise in the context of many disciplines. Lorenz (1963) demonstrated chaotic behavior in a dynamical system consisting of three differential equations that describe a horizontal fluid heated from below, i.e. a simple description of the dynamical behavior of the atmosphere subject to convective heating. He demonstrated that the outcome of the equations was extremely sensitive to initial conditions. Two trajectories that were initially very close quickly diverged until all resemblance disappeared and the trajectories were quite independent of their initial conditions. This has come to be known as the *butterfly effect*; he argued that the flapping of a butterfly's wings was sufficient to change initial conditions enough to have large future consequences. This work was the first to mathematically demonstrate that long-range forecasting is not feasible and that weather is unpredictable.

However, chaos can arise from much simpler non-linear equations. Ecologists have demonstrated that very simple equations used to describe population dynamics exhibit chaotic behavior. One such equation, presented by May (1976), is

$$x_{t+1} = k\, x_t(1-x_t) \qquad (1)$$

where x_t is the normalized ($0 < x < 1$) value of a population at time t, x_{t+1} is the normalized value of the population at time $t+1$, and k is a constant between 0 and 4. This equation, even though very simple and deterministic, can exhibit a surprising array of dynamical behavior from stable points, to periodic behavior, to apparently random fluctuations depending on the value of k.

As shown in Figure 1, the quadratic nonlinearity of Eq. 1 produces a curve with a hump whose steepness (or degree of nonlinearity) depends on the value of k. The long-term behavior of x for varying values of k is illustrated in Figure 2. (Figure 2 was produced by iterating x for a given value of k and plotting the results, discarding the first few hundred iterations.) For $k<3$, subsequent values of x converge to a stable point, i.e. a *stable attractor*, regardless of the initial size of the population. At $k=3$, we see the first *bifurcation point* for the system, i.e., a point at which the response of the system changes dramatically. At k slightly greater than 3.0, the long-term behavior of x_{t+1} is to oscillate between two values, regardless of the initial value of x_t. At $k=3.4$, another bifurcation point is reached, and as k increases beyond 3.4, x_t oscillates first between 4

values, then 8, then 16 and so on, continually doubling its period as each new bifurcation point is encountered.

At $k > 3.57$, something strange occurs. The system jumps around randomly in a chaotic manner, never repeating itself. The defining characteristic of this chaotic behavior, however, is not its randomness, but its sensitivity to initial conditions. Figure 3 illustrates the sensitivity of x_{t+1} to initial conditions within the chaotic region of k. With $k=4.0$, the first 20 iterations of x are plotted for initial values of 0.1000 and 0.1001. The two traces track each other initially, but soon become independent and show no resemblance.

Closer inspection of Figure 2 illustrates an intricate order buried within the chaos. Deep within the chaotic region, values of x_{t+1} suddenly settle into a stable period of three at approximately $k=3.83$, and the period doubling begins again. If we choose one of these bifurcation points and magnify it, as in Figure 4, we will see that it resembles the entire diagram. In fact, if we magnify portions of this diagram, we again obtain a replica of original, and so on. This property is called self-similarity, and demonstrates how the science of fractals can come into play in chaos theory. Embedded within the disorder of chaos is order of a fractal nature. (A review of fractals is given by Garbrecht et al. 1994).

Fractals

Fractals play an important role in another aspect of chaos known as *strange attractors*. An attractor, by definition, is simply a point, line or surface to which trajectories are attracted after all initial transients die out (Ghilardi and Rosso 1990). For a pendulum, the attractor is a point. The behavior of hydrologic parameters, on the other hand, does not converge with time to a point nor to a cyclic trajectory, and the process never exactly repeats itself (Rodriguez-Iturbe et al. 1989). The attractor, if it exists, has to be an infinitely long line within a finite space which, given that it is not a cyclic trajectory, means that it has to be fractal. An attractor with fractal dimension has been termed a *strange attractor* (Gleick 1987). The interest in attractors lies primarily in the fact that the nature of the attractor provides extensive information about the time behavior and nature of the natural system (Nicolis and Nicolis 1984).

Chaotic Analysis

Studying the time series from a known equation (such as Eq. 1) can be enlightening, but in many chaotic systems the underlying equations controlling response is not known. In hydrology, we want to determine whether a naturally occurring time series is truly stochastic or if it has a chaotic dimension to it. The dimensionality of the strange attractor can be determined based on analysis of time series data. However, chaotic structure is not apparent by looking at the dynamics in the conventional way, that is, correlation or spectral analysis; one must search for chaotic structure in phase space. For example, starting with rainfall as a function of time R(t), a trajectory in p-dimensional phase space can be constructed by taking as coordinates R(t), R(t+τ), R(t+2τ),...,R(t+(p-1)τ) where τ is an appropriate time delay. Techniques to analyze data in phase space have been developed to distinguish chaotic record from a stochastic one. Two commonly used are the Grassberger-Procaccia algorithm, GPA (Grassberger and Procaccia 1983) and the Lyapunov algorithm (Packard et al. 1980, Wolf et al. 1985).

The Lyapunov algorithm may be used to measure the sensitivity of a system to its initial conditions. If a system is allowed to evolve from two slightly different states, x and $x+\varepsilon$, then after n iterations, their divergence can be approximated by (Baker and Golub 1990)

$$\varepsilon(n) \approx \varepsilon e^{\lambda n} \tag{2}$$

The Lyapunov exponent, λ, gives the average rate of departure. If λ is negative, two trajectories initially separated will converge and system is not chaotic. If λ is positive, slightly separated trajectories will diverge, indicating that the system is chaotic.

The Grassberger-Procaccia algorithm, GPA, gives an indication of the number of degrees of freedom or fractal dimension associated with a time-series. An infinitely long, stochastic time series will have an infinite number of degrees of freedom. With few degrees of freedom, low-dimensional chaotic dynamics are inferred, indicating that the time series is deterministic and controlled by a small number of variables. The system could therefore theoretically be described by a nonlinear model with a small number of parameters.

As noted by Ghilhardi and Rosso (1990) and Wilcox et al. (1991), however, caution must be exercised when applying these algorithms, especially if the data are highly correlated. Additionally, a low-dimensional strange attractor inferred from the GPA does not necessarily imply chaotic behavior. Osborne and Provenzale (1989) have shown that there are stochastic processes with power law spectra that give a low correlation dimension.

Application of Chaos Theory

The most promising application of chaos in hydrology is the determination of a strange attractor. The existence of a strange attractor with fractal dimension provides an explanation for the intrinsic variability and nature of hydrologic processes, despite its deterministic character. The strange attractor implies that very close initial conditions may lead to completely different paths of the system after a certain amount of time (Rodriguez-Iturbe et al. 1989). Furthermore, the character of the attractor gives an indication of the minimum number of variables that should be involved in the description of the system.

Scientists have tested hydrologic processes for chaotic behavior by analyzing both the time series field data and dynamical models assumed to be a representation of the real system. Both approaches have their advantages.

Chaotic Analysis of Time Series Data

A major objective in time series analysis of hydrological variables is to uncover the dynamics underlying its generation. Characterization of the underlying structural properties of the series sets the framework for the subsequent development of a time series model. It is hoped that with a sufficient understanding of the characteristic structural properties of the series, one can develop a model that could be operationally useful for data simulation.

Conventional time series analysis is usually done in a stochastic framework. In the past two decades, the stationary linear Gaussian models have dominated the time series modeling applications. Nonlinear stochastic models have been introduced in the last decade, moving time series modeling toward new directions and abandoning the assumptions of linearity and stationarity (Priestley 1980). The primary motivation for development of these models is the recognition of nonlinearity in the underlying generating mechanism of observed time series.

Chaos theory has provided new methodologies for extracting important qualitative and quantitative information from a time series (Kepenne and Nicolis 1989). An integral part of chaos theory is the phase space description of dynamics of the system generating an observed series. This involves reconstruction of a finite-dimensional picture of the temporal evolution of a time series (Packard et al. 1980). Such a picture would allow one to make inferences on the asymptotic properties of the dynamical system generating the series. The trajectories in phase space provide a description of the temporal evolution of a dynamical system. It is conjectured that the presence of an attractor in phase space may lead eventually to the convergence of the trajectories to the attractor (Greborgi et al. 1987). The nature and dimension of the attractor then provides extensive information on the temporal evolution of the variables describing the dynamic system. Properties of the attractor and the nature of the orbits in phase space can help one distinguish whether a time series is stochastic or chaotic (Grassberger and Procaccia 1983).

These developments in chaos theory have important implications for analysis and modeling of hydrometeorological series. While the traditional approach assumes a stochastic framework, a dynamical approach to time series analysis adds a new dimension. The observed series can be chaotic and hence cannot be detected by conventional methods such as correlation and spectral analysis. Therefore, a dynamical approach to the analysis of an observed time series can provide new avenues for an in-depth analysis of the structural characteristics of the series and the underlying dynamics of the process generating the series. This would consequently set the direction for subsequent model development.

Recent research has highlighted the possibilities of application of chaos theory to the analysis of hydrological, local/global weather and climate variables. Initial efforts have focused the search for chaotic behavior in the time series of rainfall (Rodriguez-Iturbe et al. 1989, Sharifi et al. 1990), streamflow (Wilcox et al. 1991), sea-level pressure (Fraedrich 1986), geopotential height (Essex et al. 1987, Kepenne and Nicolis 1989), sunshine duration (Fraedrich 1986), low-level vertical velocity components (Tsonis and Elsner 1989) , oxygen-isotope in deep sea cores (Grassberger 1986, Nicolis and Nicolis 1984) and solar time series (Kurths and Herzel 1987).

Climate. Using the GPA, Nicolis and Nicolis (1984) determined the existence of a climatic attractor of low dimensionality ($d=3.1$) based on the ^{18}O data of deep-sea core V28-238. The fact that the attractor had a fractal dimensionality provided a natural explanation of the intrinsic, non-periodic variability of the climatic system. The low-dimensionality of the attractor infers that a small number of variables is involved in the description of the system.

These results were first contradicted by Grassberger (1986) and then confirmed by Fraedrich (1986) and Essex et al. (1987). Grassberger (1986) re-analyzed the deep-sea core V28-238 data, as well as other deep-sea cores, and could not corroborate the results of Nicolis and Nicolis (1984). Grassberger warned that spuriously small dimension estimates can be obtained from using too few, too finely sampled, and too highly smoothed data (noting that the largest set of raw data of core V28-238 consisted of only 184 points). Instead of a low-dimension attractor, he found that the data were unable to give any upper bound for the dimension, while they yielded a lower bound well above $d=3$.

Based on another analysis of deep-sea core ^{18}O data, Fraedrich (1986) reported the existence of a climatic attractor with a saturation dimension of 4.4. With further analysis of daily meteorological measurements from a single weather station in Berlin, he determined the existence of low-dimensional (between 3 and 4) strange attractors for surface air pressure and sunshine duration that

varied for summer and winter. Essex et al. (1987) produced similar results based on daily meteorological observations from 1946 to 1982. Observing the warning of Grassberger (1986), they did not filter the data set and included over 108,756 values in all. They found that on short time scales (that is, decades), climate might be represented as a system with as little as seven degrees of freedom. Thus, they agreed with the original position of Nicolis and Nicolis (1984) that the atmosphere and oceans exhibit properties of a low-dimensional strange attractor.

Rainfall. The first possibility of chaotic behavior in rainfall was reported by Hense (1987) with a fractal dimension between 2.5 and 4.5. Hense (1987) cautioned that this fractal dimension did not provide a sufficient condition for chaos, so that deterministic chaos in rainfall could not be clearly assessed.

Rodriguez-Iturbe et al. (1989) analyzed a time series of 1990 points of 15-s rainfall for a storm on 25 October 1980 in Boston and gave "preliminary" support to the presence of chaotic dynamics with a strange attractor. These results were immediately criticized by Ghilardi and Rosso (1990) who identified problems arising in the assessment of deterministic chaos from the analysis of natural time series, with particular emphasis on storm events. They suggested that further research was needed to assess whether storm rainfall at a point in space was stochastic or chaotic, and a larger amount of data observed with fine resolution was required.

Rodriguez-Iturbe (1991) conducted a second analysis in which he combined the data from the 1990 Boston storm with data from three other storms and 148 years of annual rainfall observations in Genoa. With these data he concluded that the storm dynamics could be characterized by a strange attractor with a dimension of less than 4.

Runoff. The only test for chaos in runoff based on long-term data was conducted by Wilcox et al. (1991). They examined a 8800 day snowmelt runoff sequence, an example of saturation excess runoff, and found no evidence of chaos. Using the GPA, runoff was found to have many degrees of freedom and behave in a random fashion. This is consistent with the predictions made by Phillips (1992) based on theoretical equations. Wilcox et al. (1991) concluded that the apparent random behavior in snowmelt runoff was due to complex interactions between many factors and that stochastic models may be most appropriate for modeling runoff.

Chaotic Dynamic Models of Hydrology

Rodriguez-Iturbe et al. (1991) looked at the feedback between large-scale temporal patterns in soil moisture and precipitation by testing for chaotic behavior in an equation describing the evolution of soil moisture at continental spatial scales. They used phase-plots over time to show that the soil moisture balance equation was capable of exhibiting chaotic behavior even when parameters were constant over time. The equation produced approximately cyclic behavior with periodicities which did not repeat themselves exactly.

Phillips (1992) used asymptotic stability to test for chaotic behavior in runoff response to a given precipitation event based on inter-relationships between soil moisture, infiltration capacity and runoff. When soil moisture was assumed to promote runoff (saturation excess runoff), the system was stable and non-chaotic. However, when soil moisture was assumed to compete with runoff (infiltration excess runoff or Hortonian overland flow), the system was potentially chaotic. This implies that runoff is generally stable except under high rainfall intensity and low infiltration capacity conditions. Phillips (1992) also assessed the hydrologic geometry of overland flow by testing the asymptotic stability of an equation system based on the Darcy-Weisbach equation. The

system described the interactions between flow velocity, flow depth, slope and resistance and was found to be potentially chaotic. This may have particular importance with regard to erosion and sediment transport. Little field data are available to substantiate these findings, however, rainfall simulator plot data collected by Abrahams et al. (1986) were examined and the runoff response of a limited number of plots indicated possible chaotic behavior (Phillip 1992).

Challenges and Opportunities

The techniques used to determine the existence and dimensionality of attractors are still in their infancy and are very much in the research frontier of chaotic dynamics. In particular, there are problems with dimension estimates obtained from insufficient data sets. It is difficult to detect whether an attractor has been reached or not, no less the dimensionality of the given attractor. Smith (1988) showed that for a correct estimation of dimensionality, d, one would need a time series with almost 42^m points, with m the lowest integer equal to or greater than d. If d were 4, estimating d would require at least 3,112,000 points in a time series. Furthermore, determination of the dimensionality of the attractor is only the first level of knowledge to describe climate properties. The second, and perhaps more difficult level is the evaluation of the independent variables (Fraedrich 1986).

Given the limitations of techniques to detect chaos, findings show that hydrologic systems may potentially be chaotic. To date no conclusive evidence exists for the presence of chaotic behavior in hydrologic processes based on field data. However, chaos has been found to be a property of several equations used to describe hydrologic systems. Such examples of chaotic behavior are only applicable to real hydrologic systems to the extent that the equations used are a true representation of the real system. If hydrologic systems are chaotic, then continued efforts to improve the predictive capabilities of physically-based models may be futile. Future modeling efforts would need to rely solely on probabilistic and stochastic approaches. More studies of chaos based on hydrologic field data are needed before any conclusion can be reached.

If future research concludes that chaos is not an important factor in the behavior of real hydrologic systems, then the search for the perfect physically-based hydrologic model is a valid scientific endeavor. In such case, the chaotic properties exhibited by many of the equations used to describe hydrologic systems must be of concern. Models based on such equations may produce chaotic behavior and greatly increase model error, particularly for long-term simulations. Perhaps the sensitivity analyses of physically-based models should include tests for chaotic behavior.

Still, the possibility of a low-dimensional attractor in hydrology presents an opportunity for a new understanding of these processes and this research should not be discouraged. In fact, the study of non-linear chaotic dynamics in hydrology constitutes a new frontier in hydrometeorology. In the search for chaotic dynamics in hydrology, researchers need to address systems on such a scale that the physical processes are contained within the scale being addressed. Stochastic behavior usually arises from random external forces. Thus, chaotic dynamics will not likely be found in a hydrologic system driven by random external forces, i.e., runoff will not likely be chaotic if precipitation input is stochastic. For chaos, irregularity is part of the intrinsic dynamics of the system and must arise from the hydrologic processes within the scale being studied.

Appendix

In a review of mathematical models, May (1976) noted that university courses in mathematics and physics were dominated by mathematical theory pertaining to linear systems, and consequently, students were ill equipped to confront the bizarre behavior exhibited by the simplest of discrete nonlinear systems, such as Eq. 1. Yet such nonlinear systems are surely the rule, not the exception, in the biological and physical sciences. He therefore urged that people be introduced to Eq. 1 early in their mathematical education. The equation could be studied phenomenologically by iterating it on a calculator, or even by hand. Alternatively, software packages are available as a compliment to several books on chaos (Gleick 1987, Baker and Golub 1990). These software packages assist the user in exploring and understanding bifurcation diagrams, sensitivity to initial conditions, the physical meaning of Lyapunov exponents, fractals, and a host of other concepts related to the science of chaos. Such study may greatly enrich one's intuition about nonlinear systems and encourage alternative approaches to complex hydrologic analyses.

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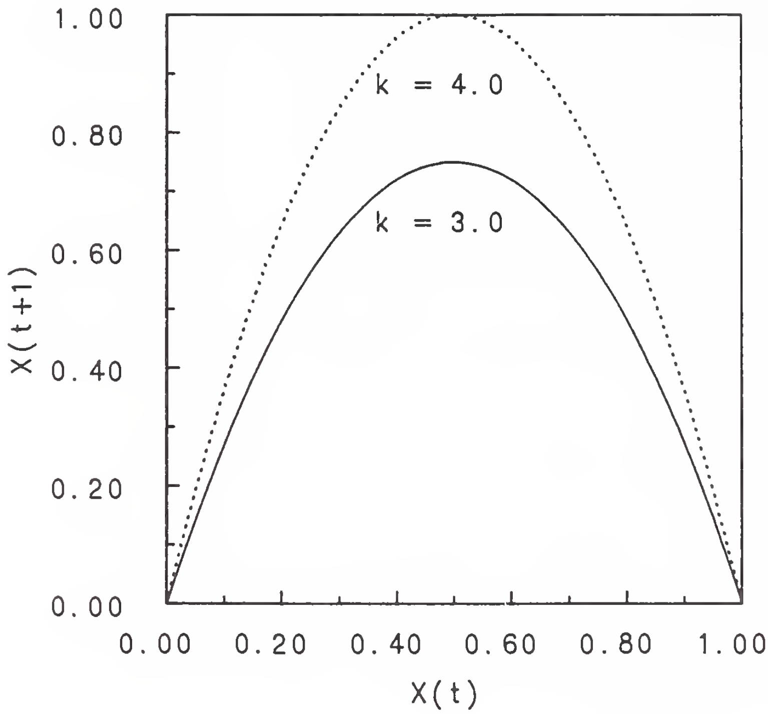

Figure 1. Form of quadratic equation: $x_{t+1} = k\, x_t(1-x_t)$

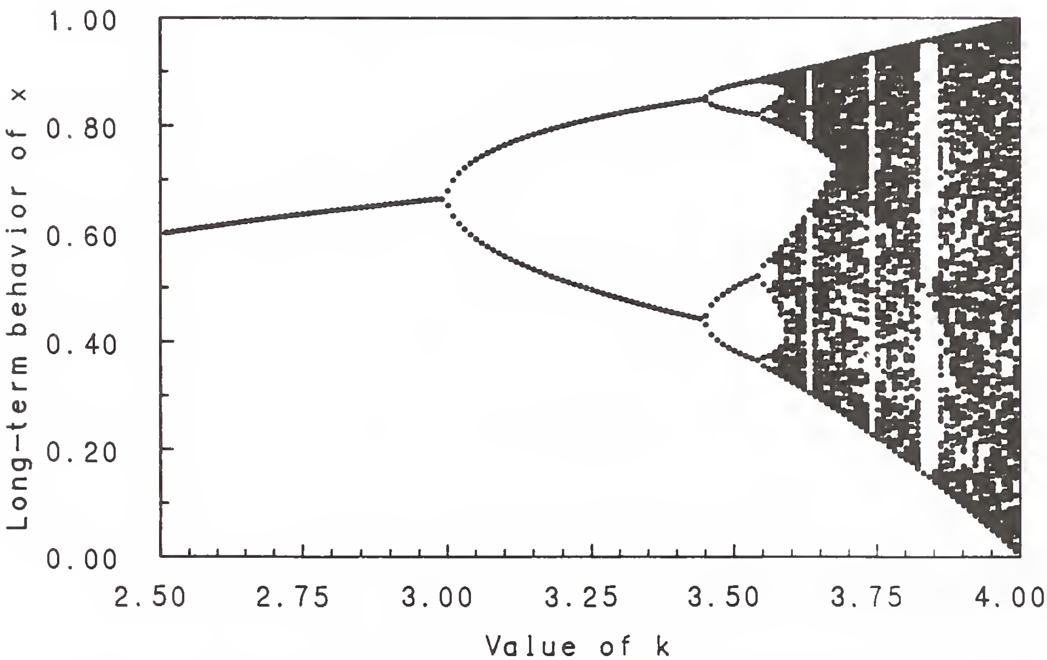

Figure 2. Bifurcation diagram for Eq. 1, showing period-doublings followed by growth of chaotic bands.

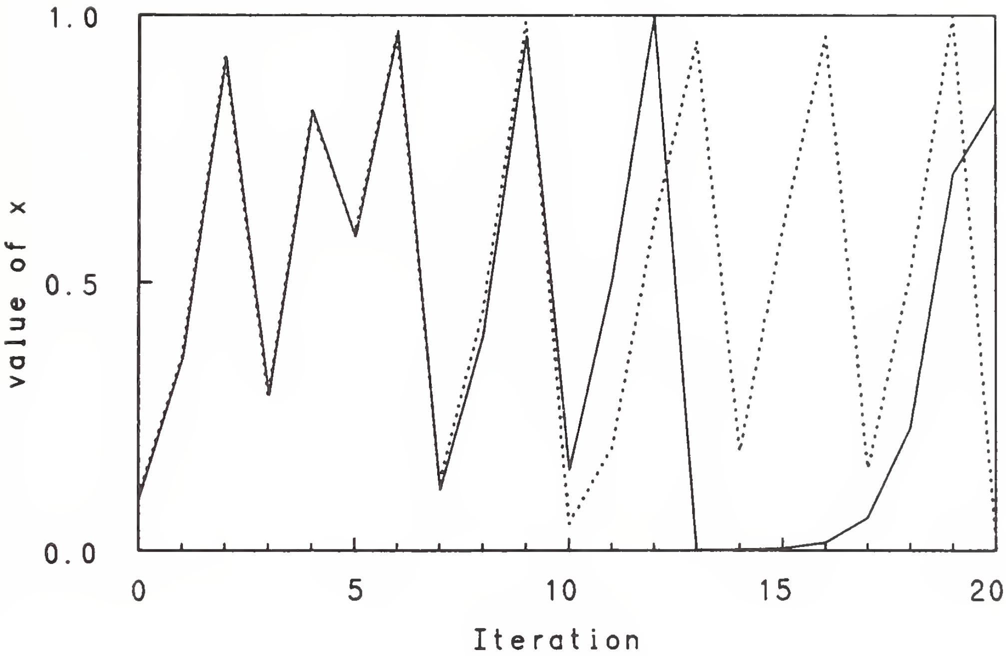

Figure 3. Successive iterations of Eq. 1 for $x_0 = 0.1000$ and 0.1001 with $k=4$, showing sensitivity to initial conditions.

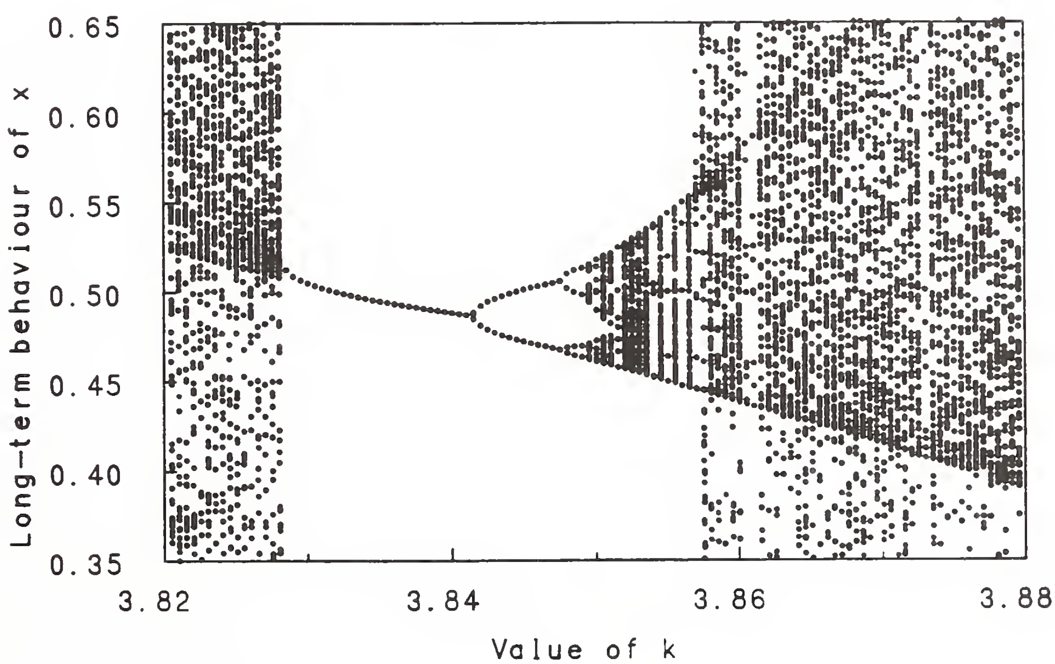

Figure 4. Blowup of Figure 2, showing self-similarity and structure that go infinitely deep.

Weather and Climate Characterization

G.L. Johnson[1], J.V. Bonta[2], D.G. Boyer[3], and G. Fernandez[4]

Summary

In this position paper we review past and present efforts in weather and climate characterization within the Agricultural Research Service (ARS), plus current, specific resource and research strengths within the ARS in this area. In addition, we identify general problem areas in which weather and climate information is required, and which the ARS can address. Identification of customers for ARS climate and climate-related information and research also is made. Specific weather and climate characterization emphases are then addressed, including the issue of spatial variability, and obtaining spatially reliable information (use of Geographic Information Systems, or GIS, etc.); temporal variability, and stochastic modeling of hydrological and meteorological time series; parameterization needs for modeling (natural resource, meteorological, etc.); watershed climate databases and studies in diverse climatic regions; and real-time and near-real-time weather information needs for forecast accentuation and improvement.

Introduction

The ARS has been involved in the collection and analysis of weather and climate information for many decades. While the collection of weather information has not been an exclusive mandate of the ARS as it has for a few federal agencies, nonetheless very valuable meteorological information has been gathered by ARS researchers, often in environments or at scales (both spatial and temporal) that make the data unique. Observations have been made at all experimental watersheds, several of which are now equipped with state-of-the-art instrumentation and telemetry, allowing previously impossible linkages with operational and research meteorologists in agencies such as the National Weather Service (NWS). Watershed data represent only a small fraction of the total amount of climatic data which ARS has collected, however. Numerous field studies have necessarily needed supplemental meteorological information. In many cases these data are nearly inaccessible, though, and are generally not as well documented as watershed climate data. The space and time scales of these data sets also are quite small.

ARS strengths in weather and climate characterization fall generally into the broad categories of research and resources. Research contributions have included leadership in the development and refinement of stochastic weather generators; detailed analyses of weather and climate, at generally smaller space and time scales than conventional meteorological analyses, and often encompassing fairly unique variables (such as evapotranspiration and soil frost); providing climatic

[1] Meteorologist, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.

[2] Hydraulic Engineer, USDA-ARS, P. O. Box 478, Coshocton, OH 43812.

[3] Hydrologist, USDA-ARS, P. O. Box 867, Beckley, WV 25802.

[4] Hydrologist, USDA-ARS, P. O. Box 1430, Durant, OK 74702.

parameterizations for natural resource and some meteorological models; and the utilization of newer tools and data for the analysis and display of raw and computed variables (such as GIS, or image processing of remotely sensed data). Resource strengths lie in our watershed databases, especially because of the plurality of data they often contain (climatic, hydrologic, ecological, etc.); extremely accurate short duration data; the long time series which exist for many of the databases; present, real-time data acquisition systems; the diversity of climatic regions represented by the total ARS database; and the linkages which ARS personnel have developed for fusing these data with models and decision support systems, making them both available and usable to decision makers.

With these capabilities, ARS stands in a position to maintain leadership in some areas and to take initiative in a few others. ARS research must, in large measure, be driven by the needs of our customers. Identification of these customers and of their requirements for weather and climate information to solve specific problems, whether it be in raw, processed or applied form, must be given high priority. Problem solving *per se* must also be balanced by creative research where the scientist is given flexibility to pursue ideas which may (and often do) result in significant advances in knowledge and, ultimately, solve problems.

Our customers are quite wide-ranging, and each ARS unit must identify those groups and individuals with which it will work most closely. There are broader issues and problems, though, which cut across geographic, political and discipline lines and which, to solve, will require the collective resources and research capabilities of at least several ARS units (separately or in combination with other agencies).

Customers include farmers and ranchers (individuals and cooperatives); federal agencies, including the Soil Conservation Service (SCS), the Bureau of Land Management (BLM), the NWS, and many others; engineers; mining interests; policy makers (including federal and state legislators, other elected officials, special interest groups); state and local agencies; private consultants; and other researchers, including those at other state and federal agencies and at universities.

Each of these customers have identifiable problems which society is dictating they must address, and in many cases the ARS has the unique expertise in weather and climate characterization to help solve these problems. Major problem areas (both traditional and those now emerging) which require meteorological inputs include:

- Water Quality, including pollutant concentration and transport
- Land management evaluation
- Design of engineering structures
- Climate change impacts on agricultural production
- Agricultural chemical usage
- Water and wind erosion
- Rehabilitation of burned areas and other land restoration efforts
- Hazardous waste management
- Surface mining management
- Water supply and management
- Hydroelectric and steam power generation
- Flood forecasting and management
- Drought forecasting and mitigation
- Wildlife management

For each of these problems, weather and climate information over a range of space and time scales is required. Some problems require unique sets of data or problem-solving approaches while others have complementary needs. Some problems will directly utilize weather or climate information or technology (such as real-time watershed weather information to NWS forecasters, or the estimation of erosion potential using ARS watershed breakpoint precipitation data), while others will more circuitously integrate these (such as developing more accurate or reasonable parameterizations of sub-grid scale variables or processes for input to regional or global scale climate models which, in turn, will be used to estimate climate change impacts on vegetation, burn potential, water yield, etc.).

A systematic analysis of these and other relevant problems, including determination of approaches currently being used to solve them, critical gaps in both current knowledge and technology transfer which are limiting solutions to them, and recommendations on the most relevant research areas for ARS to pursue in light of this information is thus in order.

Scientific Challenges and Research Opportunities

Spatially Reliable Information

Weather and climate information that can be used with a known degree of confidence, at the user's scale, can be called spatially reliable. Reliable weather and climate information can assist decision makers in their endeavors to protect crops, make intelligent irrigation decisions, make water supply forecasts, predict subsurface contaminant flow pathways, etc. Use of information that is not reliable can result in crop or livestock loss, reduced crop or livestock productivity, stressed water supply systems, excessive soil loss, aquifer contamination, etc. In other words, the use of information that is not reliable costs society a great deal of money.

Local and regional topographic and land use patterns play a role in determining the spatial variability of weather and climate systems. On a local scale, topographic conditions modify radiation, temperature, wind and precipitation patterns. There also are associated pattern developments in evapotranspiration processes. Regionally, land use patterns and topography are related to broader scale weather and climate systems. For example, Avissar and Pielke (1989) developed a parameterization of sub-grid scale land surface heterogeneities and found significant mesoscale circulation impacts in regional atmospheric processes.

Geographic information systems (GIS) are computer systems capable of working with and displaying geographically referenced information. Spatial representation of weather and climate data lends itself well to GIS. GIS offers the ability to study associations between weather and climate patterns and other geographically referenced information.

The ARS can take the lead in interfacing GIS with weather and climate simulation models to provide timely spatial information to resource managers and farmers. Research on extrapolation and interpolation methods to extend the usefulness of point predictions of weather parameters would provide a valuable tool for many weather-related activities. Indeed, a GIS-based system of estimating precipitation in any terrain by objectively defining the appropriate scale is but one example of this type of work now underway (Daly and Neilson 1992).

Coupling GIS technology with short-term forecasting of variables such as precipitation (Browning and Collier 1989) would allow farmers and resource managers to make timely decisions. Some of the agricultural benefits of accurate short-term forecasts include improved efficiency of crop

spraying, harvesting, farm management and irrigation. These forecasts would also offer the opportunity to save plant and animal life by controlling disease. Methods need to be found , though, to make forecast information available and useful at the management scale. There would also be decided benefits in more accurate maximum and minimum temperature, dewpoint and relative humidity forecasts, to name but a few.

Spatial description methodology research is needed to better define evapotranspiration and available soil water. Small scale description of those parameters would allow managers to more effectively manage resource units. For example, a farmer could avoid nutrient additions to farm areas not suited for those additions because of moisture conditions. A more precise spatial description of evapotranspiration flux could be used in water budgeting models, to improve both irrigation control and crop production predictions.

Taking advantage of new technologies will allow ARS to move ahead with a national initiative on spatially representative weather and climate modeling that will benefit farmers and resource managers. The potential benefits include better controls on protecting the environment and managing resources more efficiently. In addition, spatially representative information will be necessary for development, refinement and validation of global change models.

Temporal Variability and Stochastic Modeling

An essential task in time series analysis and modeling of weather and climate variables and derived parameters is to determine the significant dynamical characteristics underlying its generation. An adequate characterization of the structural properties would then would set the framework for the subsequent modeling. The time series model could then be used for data simulation and short-term prediction.

The need to develop stochastic models for weather and climate variables is of prime importance. Current natural resource models require climate data inputs. In most cases, these data are unavailable for the given site under study. If available, the data series may not be of adequate length. It may be of unreliable quality and hence may not be suitable for the application at hand. In this case, stochastic models could be used to provide data series that have statistically comparable characteristics as that of the observed series. The ARS has taken the lead in stochastic generation of climate variables in two widely-used models--USCLIMATE (Hanson et al. 1993) and CLIGEN (Nicks and Gander 1993).

The development of stochastic models have traditionally been done in the linear domain. Virtually, in the last two decades the class of linear Gaussian models (e.g. ARMA) have dominated time series modeling applications (Box and Jenkins 1970). The success of linear Gaussian modeling can be attributed primarily to simple equations that are readily understood, a well developed theory for statistical inference, and the availability of various computer packages which are well within reach of modelers (Tong 1990).

On the other hand, the use of the class of linear Gaussian models is limited by the following considerations. In view of the linearity and normality assumption, they are not ideally suitable for data series exhibiting a strong asymmetry in distribution, highly time-irreversible processes, a series exhibiting a sudden burst of a very large magnitude at irregular time intervals, and for data series with strong cyclic behavior (Tong 1990).

In the last decade, time series modeling moved in new directions. The twin assumptions of linearity and stationarity which underlie much of standard time series analysis were abandoned (Priestley 1980). Various classes of nonlinear models were introduced. Among the familiar ones that have found applications in various geophysical time series are the class of bilinear models (Granger and Anderson 1978), threshold models (Tong 1990), exponential autoregressive models (Ozaki 1981, Haggan and Ozaki 1981) and state-dependent models (Priestly 1980). The primary motivation for the development of these classes of models is the recognition of nonlinearity in the underlying generating mechanism of observed time series of natural processes. In some of these classes of models, ideas from the theory of nonlinear dynamics are the basis for model development. Properties such as limit cycles, "jump" phenomena and amplitude-dependent frequency can be exhibited by some of these models (Tong 1983).

These developments in time series analysis and modeling offer alternative methodologies for characterizing the temporal variability of weather and climate parameters. The complexities in the interaction between land and atmospheric processes are manifested in considerable spatial and temporal variabilities in the observed parameters. It is now well established that the underlying generating mechanism of the observed time series of weather and climate parameters is nonlinear.

With the recent developments in the theory of dynamical systems, the state of time series analysis and weather and climate parameter modeling can be put into new perspective. Chaos theory has provided techniques by which important qualitative information can be extracted from experimental time series (Kepenne and Nicolis 1989). An important tool is the phase space description of a time series (Packard et al. 1980). This involves reconstruction of a finite-dimensional picture of the temporal evolution of a time series, which allows inference on the asymptotic properties of the dynamical system generating the series. These properties, in turn, can be used to distinguish whether the process generating the series is stochastic or chaotic (e.g. Grassberger and Procaccia 1983). An implication of this is that a dynamical approach to the analysis of an observed time series could provide a new framework for an in-depth analysis of its structural characteristics and a deeper understanding of the underlying dynamics of the process generating the series. Consequently, this would set the direction for model development.

Model Parameterization Requirements

Watershed and natural resource models. Watershed models are often used for design and evaluation objectives. One developmental requirement of any model is to be able to apply it to the size of land area on which the problem being addressed is located. Consequently, models have been developed to address problems on spatial scales from farm fields to watersheds of thousands of hectares. The scale of the model and the problem being addressed, in turn, dictate the types of required climatological inputs for the model. Lack of data, in addition to the significant amount of time required to assemble the detailed climatological and physical data inputs often required by models necessitates the estimation of inputs. These estimates come from analysis of measured data covering many temporal and spatial scales.

In order to assess current climatological characterization requirements for watershed models, and to determine projected needs for characterization, a small sample of watershed models was examined. Phone interviews to individual developers and model documentation provided the information. The models considered were CREAMS, RZWQM, Opus, GLEAMS, SWRRB, SWAT, ANSWERS, EPIC, and WEPP. Nearly all models require climatological inputs (e.g., precipitation, minimum and maximum temperature, etc.) on a daily basis. Some of these models have weather generators to synthesize these values. Some models require, or have options to use, short-time increment rainfall

intensity data. A need common to nearly all models is the development of a method to characterize rainfall hyetographs using available data. Methods to accomplish this task that are being considered include disaggregation schemes, other synthetic-generation methods, or the simple use of measured data. For the larger watershed models, spatial distribution of, and spatially-correlated, hyetographs are important research needs. Another research need highlighted by use of Opus (V. Ferreira, personal communication 1993) is the development of a breakpoint rainfall hyetograph, and not just an equal-time-interval hyetograph. It was found that by using Opus with equal-time-interval data for fixed durations from 1 to 15 min the model yielded significantly different results for different sampling durations.

While the above briefly examines research needs regarding climatological characterization for watershed models, field studies to obtain fundamental knowledge and to identify and quantify climatological variables and their measured effects on different hydrologic processes can guide model development. Lysimeters, small runoff plots, small and large experimental watersheds, heavily instrumented sites, and more detailed data collected with data loggers could yield important results. Unexpected observations are often made that are very important, or can lead to other areas of research. Important variables and processes can be included or excluded from watershed models, and model simplification can be made, based on these results.

Research needs for currently available models have been highlighted above. However, developing simpler models to reduce input requirements is another area of research that can be fruitful in terms of solving particular agricultural problems. It has been documented that some simpler watershed models perform as well as more complex models.

Most watershed models are deterministic; that is, a process is represented by a set of fixed values for variables. However, it is known that climatological and watershed physical features vary spatially over short distances, and can be represented by frequency distributions. Models that consider spatial variability through such distributions may also require climatological characterization through the use of frequency distributions that include spatial correlation, etc.

In summary, examination of future plans for the small sample of currently available watershed models showed that climatological characterization needs will focus on precipitation. In particular, research on precipitation characterization of short-time-increment hyetographs is needed. It also appears that the development of breakpoint characterization is needed rather than equal-time-interval characterization. Another need is for adequate spatial characterization of precipitation. Concurrently, fundamental research on climatological variabilities and their importance on watershed processes need to be established. Finally, alternative modeling strategies that consider natural variability of phenomena need to be investigated. These alternative methods will require other types of characterization of climatological inputs than those used now.

Atmospheric models. Accurate meteorological data over a variety of time and space scales are needed by atmospheric modelers. These data are used for model calibration and validation, and for estimation of parameters at grid points. Models necessarily need smoothed data as input, which means variability must be accounted for in some fashion. In homogeneous environments this is comparatively easy, but where land surface heterogeneity is large meteorological variability also will be large and, thus, smoothing or interpolation techniques may fail to capture important processes operating at sub-grid scales. Many of the effects are nonlinear, which further complicates parameterization (Pielke et al. 1991). There is also the looming question of scale which must be addressed with (Wood and Lakshmi 1993).

Regarding scale, data sets comprising information from both individual watersheds and from multiple ARS watersheds should be assembled, and could be used to test popular hypotheses. In some cases existing data will need to be supplemented (for instance, ET, soil moisture, etc.). Again, GIS technology can be a powerful tool for these types of analyses. Projects can involve individuals or small groups. In other cases, large-scale campaigns such as Monsoon '90 (Kustas et al. 1991) are more appropriate to answer broader sets of questions.

The estimation of water and energy fluxes over a range of scales and environments is thus a challenge for the atmospheric modeling community (see also sections on remote sensing and land/atmosphere interactions). The ARS can, and should, be intimately involved with these modelers either in assembling and analyzing existing data from watersheds and other research locations, or in designing field experiments. In particular, much more needs to be known about the horizontal gradient of sensible heat flux and its relationship to land surface conditions (elevation, aspect, slope, soil moisture, vegetation cover, etc). In this same way, the ARS can take the lead in assessing and extending the validity of surface similarity theory to relatively small scale inhomogeneities (Avissar and Pielke 1989). Traditionally, temperature and precipitation data have been collected at watersheds, but information on wind and other variables should be considered.

A final arena of ARS involvement with atmospheric modelers may be in downscaling larger scale information, such as from global climate models (GCM's). Climatic and hydrologic data from ARS watersheds can be important in testing down-scale approaches and validating their output, whether they be statistical (Karl et al. 1990, von Storch et al. 1993) or dynamical in nature (Giorgi 1990).

Watershed Climate Database Analyses

The ARS maintains a data base comprising mainly precipitation and runoff records. According to Jane Thurman, computer systems analyst at the Water Data Center (WDC) in Beltsville, MD, the ARS has available to the public 8509 station-years of breakpoint precipitation record and 5286 station-years of detailed runoff record. These data were measured across the U.S., covering all climatological conditions, some dating back to the 1930's. Furthermore, there are 4600 station-years of daily precipitation data for the mid-continent area. The breakpoint characteristic of the precipitation data makes it one of the best data sets in the world for investigating short-time-increment rainfall characterization methods and spatial characterization schemes. The precipitation data set, in particular, can be used to directly address the needs of watershed models discussed above.

While this data base will be helpful to find solutions to some of the precipitation-characterization problems mentioned earlier, watershed modeling data requirements demand more than is currently available from the WDC. Model development and validation increasingly require a wide variety of data, including information on water chemistry, soils, soil moisture, temperature, solar radiation, groundwater levels, and many others. Many of these data sets probably exist at the various ARS locations, but they are not as readily available from a single source, such as the WDC precipitation and runoff data base. Individual ARS locations are involved in special data-collection efforts that could eventually be incorporated into a central data base after publications using these data have been written. In some instances, special efforts are made by the WDC to assemble data sets with many of the location-based data for particular purposes. A major ARS effort is needed to assemble all types of data in a easy-to-use system that can be queried to select data sets with specific attributes. This would make the 18000+ station years of data at the WDC even more valuable.

Quality issues need to be addressed when analyzing data. While it is believed that the data at the WDC are of high quality, annotations on the quality of data, the types of instruments used, location changes, etc. (so-called metadata) are important but presently lacking. Furthermore, one must ask a more fundamental question--what is being measured? For example, a study performed by McGuinness (1966) compared rain gage catch with lysimeter catch. He found that lysimeter catch was, on average, 1.06 times that of a standard rain gage during the summer, and 1.27 times more during the winter. The difference was attributed to the effects of wind around the rain gage on the measurement being taken. Among many researchers investigating rain gage catch problems, Hanson (1989) compared two different shielded rain gage techniques and found that shielded gages caught significantly more precipitation than unshielded gages. Optical rain gages show promise for accurately measuring rainfall and water-equivalent rates when in the form of snow, and detecting precipitation type, but these are currently very expensive instruments. Studies of the effects of precipitation measurement on runoff and other variables are important to modeling efforts because incorrect "actual" precipitation inputs can magnify errors in simulated runoff rates, etc. By using available data collected with standard gages, parameter distortion may occur when selecting values in watershed models. Research is needed into methods to accurately measure precipitation to address these problems.

The ARS has a unique combination of physical and human resources at its disposal. The agency has one of the best short-time-increment precipitation data sets and the best collection of small agricultural watershed runoff data (covering a wide range of climates, land uses and physical characteristics) in the world. Information collected on other variables such as the physical characterization of soils, water chemistry, groundwater, wind, snowfall and snow distribution, etc., if organized, would undoubtedly result in an unparalleled data set for investigating basic watershed processes and climate interactions, and for developing and validating watershed models over a wide range of conditions. Even more imperative than data organization is the need for fundamental research on techniques for measuring precipitation and other climatologic parameters. The ARS has a group of highly qualified scientists to conduct this research.

Forecast Improvement and Enhancement

ARS weather and climate information can, should and, in some cases, is being used in the development, improvement and utilization of both short range and long range forecasts. Meteorological information from watersheds and other well-instrumented sites is especially valuable, often because of data quality, data density, the type of data collected (along with companion data, such as runoff) and location. ARS data are often representative of regions for which accurate data are simply not available (such as a mountain valley, or a large agricultural field).

In some locations the ARS is already involved with the NWS in mesoscale forecast improvement, either through cooperative studies in the utilization of new, doppler radar products, or in supplying real-time meteorological information for radar product adjustment and forecast improvement. A mutually beneficial relationship exists at these locations in which the NWS provides more accurate information and forecasts, the ARS has access to a wider range of data and research possibilities, and society benefits from improved forecasts and warnings.

There is now serious interest within the meteorological and climatological communities regarding applications development of their products. Recent meetings and workshops attest to this, including the NOAA-sponsored workshop on Environmental Information Needs for Precipitation-Sensitive Systems in Boulder, CO in May, 1993 and a meeting on the utilization of natural resource models using real-time climate data and long range forecast products for land management decisions,

sponsored by and held at the Western Regional Climate Center in Reno, NV in August, 1993. In addition, the Climate Analysis Center (CAC) of the NWS is now poised to produce long lead-time forecasts (90 days to one year) based on a coupled ocean-atmosphere model (B. Meisner and N. Strommen, personal communication 1993) incorporating, among other things, information on El Nino-Southern Oscillation (ENSO), which has fairly well-documented effects on global weather. The ARS can be an integral participant in model validation and utilization. For instance, watershed models could be run using CAC-produced predicted values, or these seasonal and annual forecast values could be used to adjust parameters in stochastic climate generators (Woolhiser et al. 1993) which, in turn, could be used to drive models. The integration of forecast information into models and, ultimately, decision support systems, is thus an area of research which ARS should strongly consider given our natural resource and hydrologic modeling strengths, and unique and high quality climate and hydrologic databases.

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Water Quality and Agricultural Hydrology Opportunities in Watershed Research

C.C. Truman[1], J.A. Daniel[2], R.R. Schnabel[3], and M.J. Shipitalo[4]

Summary

How agriculture influences water chemistry/quality continues to be an important issue within USDA-ARS. Much time and money have been spent planning and conducting water quality research in the past (ie. Presidential Initiative on Water Quality). Unanswered questions still exist about water quality, especially at a watershed scale. The purpose of this paper is to show where ARS is in terms of water quality and agricultural watershed research, and to provide ideas or suggestions about what water quality and watershed research questions should be addressed in the next 10-15 years by ARS scientists. Water chemistry/quality and agricultural hydrology issues to be covered in this paper include: fundamental/process research, modeling efforts, management practices, data bases, and ARS philosophy.

Introduction

The Agricultural Research Service Program Plan (1992-1998) has defined policy for water quality research conducted by USDA-ARS scientists. The program states that: 1) researchers are to balance efforts between fundamental and applied research to solve agricultural problems, 2) research should have a long-term nature to it, and 3) interdisciplinary research teams will redirect research objectives as needed to ensure that the research is efficiently focused and that the research provides maximum benefits. ARS policy statement for water quality research also includes reducing or eliminating pollution from agricultural lands and developing management practices that protect the environment. Research is to be conducted on surface and ground water as well as point and nonpoint source pollution by agrichemicals (nutrients and pesticides).

Water quality research within ARS involves fundamental and applied research with modeling and experimental approaches. Experimental research is conducted on many scales: soil core/block, field or laboratory plots, field, and watershed scales. Water quality research involves process studies on hydrology, sedimentation, pesticides and nutrients, salinity, animal waste, forestry, and riparian zones. Examples of this work include: adsorption/desorption kinetics, pesticide and metabolite degradation rates, plant uptake, and importance of macropore flow on agrichemical transport through and within the soil profile.

[1] Soil Scientist, USDA-ARS, P. O. Box 946, Tifton, GA 31793.
[2] Geologist, USDA-ARS, P. O. Box 1430, Durant, OK 74702.
[3] Soil Scientist, USDA-ARS, Hastings Road, University Park, PA 16802.
[4] Soil Scientist, USDA-ARS, P. O. Box 478, Coshocton, OH 43812.

ARS has management research being conducted dealing with organic matter and nutrient cycling, erosion at different scales as a function of management practices, influence of filter strips on agrichemical removal and transport, and influence of animal waste and irrigation on surface and ground water quality. An example of a group of researchers working on management effects on agrichemical transport is the Management System Evaluation Areas (MSEA's). These projects will provide data for looking at effects of management practices on agrichemical contamination of surface and ground water systems. Even though selected management practices (or best management practices) can help us conserve soil and water resources and reduce environmental degradation, we must know the fundamentals and mechanics behind how these management practices work in order to extend them past specific sites in which they were evaluated.

Most watershed planning and evaluation methods use computer models, a technology that ARS has considerable expertise and many ongoing efforts. ARS models, such as WEPP, GLEAMS, EPIC, SWRRB, AGNPS, etc., help us organize our thoughts about landscape components (grid pieces and/or subwatersheds), deal with the mechanics of erosion, agrichemical transport, and different management practices, and help us answer certain questions (ie. the effect of ...) that otherwise would be too time consuming and costly to address experimentally, especially at a watershed scale. In the future, ARS researchers must maintain a balance between modeling and experimental research. Also, watershed models must be able to represent dominant processes controlling runoff, sediment, and agrichemical movement within a watershed to accurately represent the impact of various management alternatives.

Evaluating hydrology and water quality questions at a watershed scale requires an understanding of the interactions of soil, water, crops/vegetation, climate, sediment, etc. in time and space. ARS has substantial resources to answer these questions because it has researchers with different backgrounds, facilities, data bases, and funding already in place. Water quality research requires expertise in many areas (soil science, hydrology, engineering, chemistry, biology, ecology, and weed science), and ARS has researchers with these backgrounds to work on water quality problems associated with soils (infiltration, saturated and unsaturated flow, and frozen soils) (Rawls and Brakensiek 1982), evapotranspiration (plant uptake, and irrigation) (Dowler et al. 1982, Spencer et al. 1985), precipitation (snow melt, rainfall intensity, duration, and frequency) (Sharpley 1985, Willis et al. 1980), and erosion mechanics (runoff/overland flow, concentrated flow, and sediment transport) (Foster et al. 1980, Baker and Laflen 1979, Pionke 1977, McDowell et al. 1981). The expertise is also in place to model different systems, instrument plots, fields, and watersheds, simulate rainfall, do chemical analyses of agrichemicals, and study spatial variability.

One of ARS's most valuable resources is the number of research plots and watersheds located throughout the US. Over the years, ARS researchers have collected data from over 600 watersheds. Many of these watersheds, with a range of land use scenarios (crops, pasture/range, and woodland), are gauged to monitor runoff and sediment yield, while a few others are gauged to include the movement of solutes, nutrients, and pesticides. Maintaining these sites provides many advantages including framework for long-term and short-term water quality research questions, background data bases, and an avenue for researchers to cooperate on multi-disciplinary water quality studies.

In terms of laboratory facilities, ARS has some of the best nutrient and pesticide chemistry laboratories in the country. ARS has selected laboratories that are set up to study interactions between surface and ground waters, erosion with rainfall simulators, lake water quality, water and agrichemical movement in riparian zones, preferential and macropore flow, remote sensing, and geographic information and image processing systems.

Extensive data bases have been produced by ARS researchers at various locations including those associated with productivity, rainfall/runoff characteristics, erosion and sediment transport, soil water content and movement, solute transport, nutrient and pesticide chemistry, and groundwater. Also included in these data bases are supportive information such as soils information, land use data, and meteorological information. These data bases are extremely important as we look at future needs and directions for water quality and watershed hydrology research in the next 10-15 years (given that we understand the limitations and constraints in each data base in terms of limitations in theory and differences in methodology). A continued effort is needed to record and organize as much of the data collected from watersheds operated by ARS researchers both from existing watersheds and from those established in the future. Data bases should also be made open to other researchers in ARS and other state and federal agencies. However, ARS must become committed to data collection/monitoring from watersheds in terms of providing resources (personnel and dollars) and an avenue for career advancement for persons working on this non-rewarding (yet valuable) endeavor. Also, an ARS committee needs to be established to set criteria and overall guidelines for water quality data sets collected.

Scientific Challenges

In this section, we have listed and discussed selected research areas or topics where critical gaps exist in our understanding, especially on a watershed scale.

In many landscapes and watersheds, how water is partitioned at the soil surface will have a major impact on agrichemical movement within and from the watershed. From a fundamental hydrology standpoint, we need to know 1) which rainfall and soil properties influence water infiltration and runoff, and 2) how soil properties change as one moves from one part of the landscape or watershed to another. Understanding this will help us identify dominant pathways (surface, vertical infiltration/percolation, lateral subsurface flow, groundwater, etc.) in which water travels within and from a landscape or watershed. With this knowledge, we will also be better able to quantify the movement of water through all parts/areas of the watershed. Understanding how water is partitioned will also help us understand how agrichemicals are partitioned. However, chemical properties, like the partitioning coefficient, will give us some indication as to what mode of transport (solution or solid phase) the chemical will be transported. Increased experimentation is needed to help answer initial questions in this area. Modeling efforts will also benefit from this increased knowledge.

We need a better understanding of factors influencing pesticide degradation rates, including their metabolites, for the entire transport pathway within the watershed. Critical gaps exist in our understanding of pesticide degradation rates in the vadose zone and groundwater. Even less is known about the rate at which metabolites form and about their characteristics. Possibly the most limiting information on pesticide degradation is how biological processes influence pesticide degradation in the root and vadose zones and groundwater. A good example is that atrazine degradation rates reported from different parts of the country vary considerably ($t_{1/2}$=10 to 120 d) (Leonard et al. 1988, 1991; Ghadiri et al. 1984, Hiltbold and Buchanan 1977). We need to understand how a given chemical can have that much variability in its degradation rate at different sites and depths. Pesticide transport models would benefit greatly if more accurate rate equations were available.

For watersheds across the U.S., a better understanding is needed on how phosphorus (P) is transported through a watershed and how P should be managed to ensure crop productivity and at

the same time protect the environment. Phosphorus is mainly responsible for accelerated eutrophication of off-site surface waters (eutrophication limited by P rather than nitrogen). Dominant transport agents for P are runoff (solution phase) and soil loss (particulate phase). We need to understand how fundamental erosion mechanics (especially particle selectivity, sediment size distribution, and runoff generation) influence P partitioning and transport. Because of the role P plays in eutrophication, we must consider the bioavailability of P in runoff and P associated with sediment. Most soluble P is bioavailable immediately, whereas particulate P can be a long-term source of bioavailable P. Soluble P can be transported by runoff and subsurface flow. Soil and hydraulic factors that influence soluble P partitioning between runoff or subsurface flow and soluble P transport as subsurface flow need to be better understood. Sources of P include commercial fertilizers and animal manures. Generally, manures are applied as a means of disposal. Efficient ways are needed to better utilize P in manures especially in terms of considering agricultural lands with soils, geology, background soil P levels, etc. suitable for manure application, basing manure applications on P rather than nitrogen content, and considering nutrient uptake by crops. More attention needs to be given to management strategies that identify and control nonpoint P losses from sensitive areas within a watershed where potential for P losses are high. We need to develop and implement management practices that minimize P build-up in surface soils in excess of crop requirements and consider off-site effects of transported P.

From a water quality standpoint, the role of riparian zones in controlling non-point source pollutants moving in and through watersheds is not well understood. We must understand the physical, chemical, and biological processes involved in riparian zones, and use this knowledge to improve our understanding of agrichemical and sediment transport within and through these zones. Riparian zones should not be used solely to control non-point source pollution from agricultural fields, but rather should be studied as part of the overall transport pathways within a watershed. We also need to make sure that watershed scale models represent dominant processes occurring within riparian zones. Much more experimental (fundamental and management) and modeling research is needed in this area, which should increase our understanding of how water, sediment, and agrichemicals move in watersheds. Also, data bases should be accurately and completely developed from riparian zone research.

Soil erosion and sedimentation decreases site productivity, degrades water supplies, reduces reservoir storage capacities, and alters riparian zones. A better understanding of sediment transport processes (including deposition and re-entrainment) at all scales is needed. Also, experimental data on particle selectivity, sediment size distributions, and how sediment size distributions change with travel distance continue to be limiting. Increased knowledge about sediment transport processes will help us evaluate and predict sediment yield from fields and watersheds, and predict environmental effects of alternative land use activities. Better understanding of particle selectivity and sediment size distributions helps us predict agrichemical transport, especially for those chemicals with large partitioning coefficients which are likely to be transported in the solid phase. Models that predict sediment and agrichemical yields from fields and watersheds will benefit from a better description of processes controlling sediment transport, particularly particle selectivity and sediment size distributions.

Because of water quality problems and pollution attributed to agriculture, ARS researchers have had to provide information on the utility of "best-management-practices" (BMPs) before we fully understand all processes and mechanisms charactersitic of the specific BMP. Until we understand basic processes of a specific BMP, that management practice will not likely be able to be extended past the land unit on which it was developed and evaluated. BMPs influence runoff and transport of

sediment and agrichemicals while maintaining crop productivity, however, more research is needed on the use, acceptance, and long-term nature of BMPs. There is a need to develop specific sets of BMPs for various sized land units. It is important however to keep in mind that selected BMPs developed for a given region of the country may or may not be accepted or effective in other parts of the country. Also, current research on management practices does not account for landscape linkages or "downstream" receiving waters from a watershed. An example of this is a BMP could be developed to reduce sediment delivery from an agricultural field that is part of a watershed while not controlling runoff water from that field. This can cause potential problems for streams or other receiving waters in that excessive erosion can occur.

Research Opportunities

Many basic questions remain in watershed research for understanding the fundamentals of the system being studied. We still need a better understanding of the behavior of natural water delivery systems at field and watershed scales. More information is needed on the role and importance of topographic and soil sequences of landscapes within a watershed on water and agrichemical partitioning, runoff, infiltration, percolation, lateral subsurface flow, sediment delivery, and agrichemical transport. This information could be helpful in extending certain field-scale processes to watershed scale processes. Information is needed on how intrinsic soil properties both spatially and with depth cause and influence lateral subsurface flow and preferential flow. Although progress is being made in describing and quantifying lateral subsurface flow (Ahuja et al. 1981), a better understanding of lateral subsurface flow through soils and geologic materials is essential for modeling agrichemical movement through different parts (laterally and with depth) of the watershed. Also, lateral subsurface flow influences the residence time of soil water and associated agrichemicals in any given zone (root or vadose zone). In terms of characterizing preferential flow, we must identify zones of preferential flow whether by biopores, funnel flow, macropore flow, etc., and how preferential flow alters rates of agrichemicals reaching target bodies of water, especially groundwater. Once better field data is obtained on lateral subsurface flow and preferential flow, we will gain improved understanding of basic mechanisms affecting agrichemical transport. This information can then be incorporated into models that can guide the development and refinement of BMPs.

Much progress has been made by ARS researchers involving the development of analytical simulation models. Although such models do an adequate job on water balance and runoff simulation, none adequately treat channel stability in sufficient detail to reflect watershed protection methods. Deterministic/probabalistic models, as difficult as they may be to develop, offer a good chance for prediction capability with a wide application to conditions across the country. Simulations can be used to scale processes and variables in terms of their importance to integrated watershed behavior and to reveal gaps in information on linkages between watershed processes. In addition to the continued modeling effort, there needs to be increased emphasis on risk and frequency analysis and probability. For example, we need to determine impacts of low frequency/high magnitude rainfall events on water resources. We need to better predict the probabilities of rainfall-runoff amounts occurring through different parts of a watershed and how probabilities change with different management activities. Also, we need more information on how low frequency/high magnitude rainfall events influence sediment yield and agrichemical transport, and how rainfall timing after agrichemical application affects agrichemical transport.

Development of management practices for controlling nonpoint pollution within and from agricultural watersheds will continue to be important in the next 10-15 years. In developing these

management practices, we must make sure that 1) pollutants causing off-site problems are controlled, and 2) we know enough about mechanisms and processes influenced by the management practice so that the practice can be used at other sites for which it was not developed and evaluated. Research to assess BMPs might best be conducted through collaboration with agencies that currently manage large tracts of land. Few ARS locations own or control enough land to assess BMPs. Land owner collaborators often move on to other management practices while we are still evaluating. This may be a reason to incorporate owner/operators in the design of BMP research. We also need to maintain credibility with the land owner. An alliance with progressive farmers and farm consultants could build a client base and support for our research.

Currently, data bases are not coordinated, comprehensive, or properly maintained. Most data bases are not collected or compiled with exchange between researchers in mind. ARS has a tremendous resource in the amount of data collected from selected sites throughout the country. This data will prove valuable when developing future objectives for watershed research. We need to develop a common standard for data bases to ensure accuracy and similarity among data sets and to facilitate exchange. ARS would have to commit additional funds and personnel to updating existing data bases and coordinating, managing, and insuring proper storage of future data bases.

ARS Philosophy

An additional topic that needs to be discussed if we are to successfully and efficiently proceed into the next 10-15 years of water quality and watershed hydrology research is ARS philosophy. First of all, ARS as an agency must be perceived as a creditable organization to the environmental community, and we as ARS researchers must be responsible and open/sensitive to social needs. Societal demands are increasing the need to better understand the consequences of man's activities on soil and water resources. To meet those demands, ARS researchers must start with basic science. ARS researchers must identify problems and develop clear objectives to address those problems. We cannot just develop monitoring programs, but obtain results that completely answer our objectives and that provide "backable" solutions. Secondly, ARS must be committed to long term research to address resource management and water quality problems at all scales of research. Thirdly, ARS must improve communication and working relationships among its own researchers. This will be essential when integrated research is needed to study "best-management-practices". Each researcher must provide his/her training and expertise, and be willing and able to contribute to a common research problem. Finally, ARS must develop closer communications and working relationships with other agencies at all levels, especially SCS. If we are to provide research answers and information to our action agency, SCS, we must communicate with them so that their needs are known and understood. Likewise, SCS must understand the research process (time requirements and constraints, costs, agency policy, etc.) so that needs can be stated in an addressable framework. For example, SCS has stated that in the area of water quality, knowledge about nutrient and pesticide transport/movement are the greatest needs. They have also prioritized their needs in terms of pollutants as follows: nutrients (N and P), pesticides, animal wastes, and sediment. They also want tools to quantify existing conditions and predict the effects of practices so they know when they have arrived at acceptable levels.

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Biological Processes and Hydrology:
Scientific Challenges and Research Opportunities

S.P. Hardegree[1], M.J. Shipitalo[2], S.S. Knight[3], and C.M. Feldhake[4]

Summary

The current hydrologic approach to characterize environmental water and heat flux does not adequately account for spatial and temporal variability in vegetation processes. Individual plant effects on hydrology are complicated by physiological and morphological determinants of water content and flux. Methods for quantifying plant water relations parameters are less familiar to hydrologists than are methods for characterizing soil and atmospheric systems. Hydrologic effects of soil fauna are largely ignored in current simulation models. Traditional issues of agricultural productivity as well as newer issues related to global change, biodiversity and natural resource conservation pose problems that require in large part "hydrologic" solutions. The spatial distribution of soil heat and water relative to plant growth are the critical factors determining agricultural productivity and the maintenance of healthy, diverse natural ecosystems. One of the major scientific challenges to hydrologists will be to establish better linkages to other fields of study and to adopt a broader research perspective than defined by traditional soil science, hydrologic and meteorological disciplines.

Introduction

Water availability and temperature are the two most important environmental parameters affecting physiological processes of land plants (Barbour et al. 1980). The spatial and temporal distributions of heat and water determine plant growth form and vegetation pattern across the landscape at all levels of resolution (Barbour and Billings 1988). Evergreen, deciduous, phreatophytic, and ephemeral growth forms have all adapted to optimize water use in their respective habitats. Water availability determines the distribution of the various life forms of grasses, forbs, shrubs and trees and their vegetative structure. Morphological characteristics of leaf shape, orientation, succulence, sclerophylly, and root distribution have all evolved to maximize efficiency of plant water use in the environment (Barbour et al. 1980). Plants have also evolved different physiological mechanisms for carbon metabolism to take advantage of different levels of water availability in the environment (Feldhake and Boyer 1993, Stout 1992).

As plants have access to water throughout the soil profile from the surface horizons to as deep as the water table, they can greatly affect the distribution and magnitude of evaporation processes in

[1] Plant Physiologist, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[2] Soil Scientist, USDA-ARS, P. O. Box 478, Coshocton, OH 43812.
[3] Ecologist, USDA-ARS, P. O. Box 1157, Oxford, MS 38655.
[4] Soil Scientist, USDA-ARS, P.O. Box 867, Beckley, WV 25802.

the hydrologic cycle (Burt and Swank 1992, Baumgartner 1967, Swank et al. 1988). Just as land is classified by vegetation type, vegetation type is in turn described by the environmental limitations to species and plant community distribution (Barbour and Billings 1988). Changes in vegetation can have large effects on water use and distribution (Swank et al. 1988, Burt and Swank 1992).

Scientific Challenges

Current Hydrologic Applications

Spatial and temporal variability of vegetation. The processes of climate, soil development, biological dispersal, and plant growth, development and competition contribute to the high spatial and temporal variability within natural plant communities (Barbour et al. 1980). Computer technology now permits continuous monitoring of hydrologic variables and data continues to accumulate as to the significant effects of vegetation distribution on hydrologic processes (Pierson and Wight 1991, Wight et al. 1991). Current simulation models of vegetation effects on soil microclimate do not acknowledge spatial variability in plant cover. The majority of soil water and temperature models are empirical, primarily address agricultural applications, and have not been validated for processes that are of critical importance to establishment, restoration, maintenance and productivity of wildland plant communities. Flerchinger and Pierson (1991) enhanced the Simultaneous Heat and Water (SHAW) model developed by Flerchinger and Saxton (1989a,b) to include the insulating influence of plant canopies on the variability of seedbed microclimatic conditions. Pierson et al. (1992) compared the SHAW model with other more empirical soil water and temperature models and determined that the more complex, process-based, approach was necessary to accurately simulate microclimatic variability in natural systems.

The three dimensional nature of soil and plant processes is not often addressed in hydrologic modelling applications. Most of our hydrologic models assume some degree of uniformity in the distribution of vegetation and resulting effects on hydrologic parameters. Ham and Kluitenberg (1993) found some assumptions inherent in one-dimensional soil models were not valid even for the relatively uniform plant distribution in a row crop. Some agricultural crop models are now available to address two-dimensional variability in below-ground processes (Pachepsky et al. 1993) but three-dimensional models may be necessary to characterize soil heat and water flux in the natural environment.

Temporal variability in plant structure and function is also inadequately addressed in current natural resource models (Blackburn and Pierson 1993). Plant function is cyclic in nature, both in morphological development and physiological function. Characterization of vegetation effects on hydrologic processes cannot necessarily be accomplished with static parameterization values.

Unlike agricultural crops that are sown in a homogenized soil environment and are harvested annually, wildland species have a cumulative influence on the hydrologic environment beyond the traditionally recognized effects of canopy cover. Rainfall simulation studies in which the vegetation is removed show canopy cover per se has little effect on hydrologic response (Simanton et al. 1991). Cover type, however, is highly correlated to hydrologic variability (Spaeth and Sosebee 1991). This variability is in great part due to properties of the system that cannot be quantified other than to link them to particular community types. Vegetation effects on hydrology are due to long term effects of plant cover on soil properties that may be difficult to quantify.

Measurement and validation of plant parameters. Validation of water flux models through the soil-plant-atmosphere system requires that we can accurately measure water relations parameters of

soil, plant and atmospheric systems. Most equations describing water flux through the soil and plant follow the same general form:

$$\text{Flux} = \text{gradient/resistance}$$

The gradient term is usually represented by the difference in water potential or concentration over space (Campbell 1977, Jones 1983). Flux and gradient values often can be measured directly and are usually used to derive an empirical estimate of resistance. Incorporation of plant water relations into hydrologic models, therefore, requires accurate measurement of plant water potential and water flux rates, both for initial determination of hydraulic resistance and for subsequent model validation. Plant water potential measurement poses some special problems that have not been adequately addressed in the scientific literature. The two most common instruments for estimating plant water potential are the pressure chamber and the thermocouple psychrometer (Turner 1981). Ritchie and Hinckley (1975) reviewed studies of 41 species in which pressure chamber measurements were compared to thermocouple psychrometer measurements and found that there was usually a difference between the two for a given plant sample. The discrepancy between instruments can be as large 1.5 MPa over the plant water potential range of 0 to -3.0 MPa (Hardegree 1989c, Kaufmann 1968). The thermocouple psychrometer is considered to be the more accurate instrument but Hardegree (1989b) determined that the relative accuracy may depend upon pre-measurement stress history of the plant. The conditions likely to exacerbate measurement errors are a high ratio of xylem to leaf symplasmic volume and high levels of water stress in the period prior to sampling (Hardegree 1989b,c). These conditions are typical of small leaved desert shrubs that occur over most of the semi-arid and arid regions of the western United States (Barbour and Billings 1988). The simple question of accurate measurement of plant water potential must be answered before valid plant process models can be incorporated into hydrologic modeling systems.

Traditional hydrologic applications usually lump soil evaporation and transpiration into a single evapotranspiration (ET) term. Plant scientists are usually more interested in processes directly related to transpiration alone, such as, stress physiology, photosynthesis and growth (Mooney et al. 1991). The Penman-Monteith approach to calculating canopy transpiration requires an estimate of stomatal conductance and leaf area index of the canopy. Plant water use, however, is ultimately controlled by physiological mechanisms within the plant. Stomatal conductance depends on the interaction of light, humidity, temperature, water availability, leaf age, phenology, stress history and position within the canopy (Iacobelli and McCaughey 1993). These processes need better representation in current hydrologic models in order to make them more relevant to vegetation management applications.

Non-plant biological interactions. *Grazing animals*. Grazing animals have a significant effect on vegetation characteristics and, therefore, on plant water use and the hydrologic cycle. Large herbivores also influence soil physical properties through surface compaction. The combination of plant removal and soil compaction on grasslands generally results in reduced infiltration capacity but the reduction is tied to intensity of grazing pressure as a function of stocking rate. Decreased infiltration and increased runoff on heavily grazed pastures can affect water quality by increasing erosion rates (Thurow et al. 1986, Weltz and Wood 1986a,b, Pluhar et al. 1987). The primary method to minimize negative hydrologic effects of grazing is to maintain adequate plant cover (Holecheck et al. 1989). Future research on grazing effects on hydrology, however, cannot rely on traditional empirical approaches. The challenge will be to define the basic processes involved in grazing effects on soil physical properties, heat and water flux in the environment.

Soil fauna. Soil scientists are instructed at the onset of their training that soils are three-dimensional natural bodies that integrate the effects of the five soil factors (i.e., parent material, climate, topography, biota, and time). Unfortunately biotic process effects of soil faunal activity on soil structure, in terms of porosity, aggregation, and aggregate stability, are often overlooked by soil physicists and hydrologists.

In conventional agricultural production systems, periodic disruption of the soil by tillage tends to obliterate the effects of faunal activity on soil structure. Additionally, removal of crop residue from the soil surface intensifies fluctuations in temperature and moisture and reduces food supply. Consequently, environmental conditions are less suitable for faunal activity and, thus, faunal populations and species diversity are often reduced by tillage. On the other hand, conservation tillage systems more closely resemble a natural ecosystem in that a continuous residue cover is maintained and the frequency and intensity of tillage operations is reduced. Under these conditions, the role of the fauna in organic matter decomposition, nutrient cycling, and soil structure formation can be enhanced with the greatest effects noted under no-till (House and Parmelee 1985). While changes in tillage operations can affect populations of a wide variety of insects and microarthropods, it is earthworms that often receive the most attention.

One of the reasons earthworms are believed to have a major influence on soil structure is because of the amounts of organic matter and soil they can process. It has been estimated that earthworms can ingest 22 to 27 Mg ha^{-1} of cow dung per year (Guild 1955) and that they can consume an annual leaf fall of 3 Mg ha^{-1} in approximately 3 months (Satchell 1967). In the process of obtaining food, earthworms ingest a considerable amount of soil and subsequently excrete this organic debris-soil mixture as casts. Estimates of cast production are quite variable and range from 1.5 to 2,600 Mg ha^{-1} yr^{-1} (Watanabe and Ruaysoongnern 1984). Moreover, field estimates of casting activity are probably gross underestimates of actual amounts ingested since many species do not commonly cast onto the soil surface, and sub-surface casting is often ignored (Edwards and Lofty 1977).

Also important from a hydrologic perspective, is the burrowing activity of earthworms. Estimates of the number of earthworm burrows in temperate region soils range as high as 100 to 800 m^{-2} (Lavelle 1988). More burrows are usually found in no-till than in cultivated fields because they are not disrupted by tillage. Under these conditions, the burrow can last longer than the earthworms which formed them (Lavelle 1988). Coincident with an increase in earthworm burrow density upon the adoption of conservation tillage practices, a change in hydrologic response of the soil is often observed. Whether this is attributable to the earthworm activity is a point of contention.

It is now generally recognized that preferential flow, in which a portion of the percolating water can bypass a large fraction of the soil volume, occurs in most soils. In particular, macropores formed by the burrow activity of earthworms have been implicated as important pathways for conducting water and chemicals due to their relatively large size, continuity, and abundance (Ehlers 1975, Steenhuis et al. 1990). Edwards et al. (1989) documented the ability of earthworms burrows to concentrate the flow of water, with the degree of concentration dependant on storm and soil characteristics. With increased amounts of water moving through a reduced volume of soil there is concern, however, that chemical transport to groundwater might increase. Laboratory studies suggest this should be primarily a concern when heavy, intense, rainfall occurs shortly after surface application of a chemical (Edwards et al. 1993), but long-term field studies are needed to prove this contention.

Numerous studies have been conducted in order to determine the effect of earthworm casting activity on soil structure, yet we still do not have quantitative information that can be applied to the field. Among the reasons for this are a lack of accurate measurements of casting rates, difficulty in measuring and defining aggregation and aggregate stability and problems associated with transferring laboratory results to field application. Most of the older work has shown that earthworm casts are more stable than uningested soil but, in most instances, the samples were oven dried prior to analysis. More recent studies, in which casts were maintained under conditions more similar to those likely to be encountered in the field, have demonstrated that earthworm casting activity initially destabilizes aggregates and improvement in aggregation requires aging for several days or weeks or a drying cycle (Barois et al. 1993, Marinissen and Dexter 1990, Shipitalo and Protz 1988, 1989). This period of instability may adversely effect soil loss under some circumstances. We still do not know how long improvement in aggregate stability persists or the net effect of earthworm activity on soil aggregation.

Future research must take into consideration that earthworms burrows are not merely holes in the ground that can conduct water and that the effects of the earthworms on aggregation and porosity cannot be studied in isolation. Due to the lining of burrows with casts and bodily secretions of the worms (i.e., drilosphere) burrows can act as a sorbant and/or secondary source of nutrients and pesticides and are a zone of enhanced biological activity (Edwards et al. 1992, Stehouwer et al. 1993).

The interdependence of burrowing and aggregate stabilization is illustrated by the results of a study by Sharpley et al. (1979). When they chemically eliminated earthworms from permanent pasture plots a threefold reduction in infiltration rate and a twofold increase in runoff occurred. Even so, the amount of erosion that occurred was only one quarter of that in the plots with earthworms where an estimated 75% of the sediment originated from earthworm casts. Thus, under some conditions earthworm activity can increase erosion even while increasing infiltration and reducing runoff. Also, in some instances, increased infiltration due to earthworm burrowing activity can be undesirable. Kemper et al. (1987, 1988) found earthworm burrows contributed to excessive water losses from irrigation ditches and uneven water distribution in furrow-irrigated fields. They found management practices such as compacting the soil, using low organic matter soil in ditch construction, and adding ammonia-based fertilizer to irrigation water could help reduce these problems. Similarly, if chemical transport in earthworm burrows is found to be a problem in no-till soils, we should be able to devise management strategies, such as changing the way agri-chemicals are applied or altering formulations, in order to reduce the potential for transport.

New Hydrologic Applications

There are significant barriers to communication between the hydrologic and biological science communities. These barriers begin forming in the university environment where students are partitioned by degree programs. Hydrologists are drawn from programs that emphasize physics, inorganic chemistry, meteorology and soil science. Botany and plant physiology students can usually fulfill their soil science requirement by taking a single introductory course. Vegetation and soil/hydrologic scientists publish in different journals and attend different professional meetings. Opportunities for interaction exist, but the degree of cooperation and collaboration is not proportional to the level of interaction that takes place between plant and soil systems in the environment.

The nature of current policy and management issues will require a paradigm shift for both plant and hydrologic scientists. Traditional agricultural and hydrologic concerns have focused upon

productivity and quality of agricultural products and water supply. Agricultural scientists in the past could rely on empirical models to describe the hydrologic environment because the focus was on crop response to a relatively uniform and optimized physical environment. Hydrologists in the past may have considered vegetation to be a hydrologic variable but only to the extent that it affected the perceived "products" of infiltration, runoff and erosion. Current national issues of global change, biodiversity, and conservation of natural resources address problems that cannot be solved by traditional approaches. National concern has shifted to wildland systems that exhibit high variability in soils, vegetation and climatic regime. Indeed, maintenance of variability has itself become a high priority issue. One of the greatest scientific challenges to hydrologists will be to refocus attention on processes that affect water and heat flux relevant to the establishment, growth, distribution and productivity of natural plant communities. Lauenroth et al. (1993) underscore the importance of feedbacks between vegetation patterns and ecosystem processes. The following are some vegetation-related issues that cannot be addressed without significant new research on the interaction of vegetation, soil and atmospheric systems.

Global change. There is currently a scientific consensus that human-caused emissions of carbon dioxide, nitrous oxide, methane and chlorofluorocarbons are of sufficient magnitude to affect global climate. These gases absorb heat that would otherwise be radiated back into space and are expected to alter global patterns of temperature and precipitation. Computer models of global atmospheric processes indicate that we are currently experiencing a global temperature increase that will continue into the next century even if we significantly reduce current levels of atmospheric emissions. In addition to a general increase in global temperature, spatial and temporal patterns of temperature and precipitation are expected to shift as a result of changes in global circulation patterns (Committee on Earth Sciences 1990, Intergovernmental Panel on Climate Change 1990, National Research Council 1989).

Climate change is expected to have a large impact on water resources through its effect on the hydrologic cycle (Gleick 1989). These impacts will affect water supply to streams and groundwater but will also greatly affect soil moisture availability and use by plants. Climatic change will result in altered water requirements for irrigated crops (Adams et al. 1990, Peterson and Keller 1990) and redistribution of wildland plant species and plant community types (Huntley 1991, Bradshaw and McNeilly 1991). Historical changes in regional climate have resulted in migration or extinction of wildland plant species (Bradshaw and McNeilly 1991). Current predictions of climate indicate a much faster rate of change than would normally occur in the absence of human influences. Rapid change may limit natural species migration and adversely affect plant productivity and native plant diversity (Huntley 1991).

The current ARS Global Change Research Program contains a Climate and Hydrologic Systems component, a Biogeochemical Dynamics component and an Ecological Systems and Dynamics component. These components interact strongly in their aggregate effects on plant community dynamics. The hydrology program within ARS will be challenged to interact more closely with other system components.

Rangeland restoration. Rangelands comprise the largest component of the terrestrial ecosystem (Williams et al. 1968). Rangeland is a primary source of quality water for human consumption, irrigation and energy production. It also provides forage for livestock and wildlife, critical habitat for endangered species, and recreational opportunities for a growing population. Rangelands in the western United States have undergone relatively rapid and large scale changes in ecosystem structure over the last two centuries (Heady 1975). These changes have resulted from overgrazing, disruption

of the natural fire cycle, disturbance of riparian areas and inadvertent introduction of non-native annual and perennial plant species. Critical factors determining plant community establishment, productivity and persistence are the spatial and temporal distribution of soil heat and water relative to growth response of both desirable plant species and weedy competitors (Barbour et al. 1980, Roundy and Call 1988). Current revegetation efforts by the Bureau of Land Management and Soil Conservation Service rely only on gross approximations of species adaptation to mean annual precipitation and soil textural characteristics. While the seeding guides used by these agencies acknowledge the critical dependance of vegetation upon hydrologic variables, they do not take into account the temporal variability of heat and water flux in the seedbed. Development of technology to characterize spatial and temporal variability in seedbed microclimate would significantly advance the technology available for rangeland restoration.

Biodiversity. In the most basic sense "biodiversity" is simply a descriptive attribute of a biological system. Diversity can refer to compositional diversity, determined by species number and abundance pattern; structural diversity, the distribution of species groups that share similar physiognomic characteristics; and functional diversity, the variety of complex and interactive ecological processes inherent in most natural ecosystems (Noss 1990). In the past, land rehabilitation efforts have focused on the introduction of non-native plant materials which are relatively easy to establish and produce more forage than native species (Roundy and Call 1988). Public awareness has been changing, however, and new strategies for wildland management will have to be developed that include restoration and maintenance of native plant biodiversity as a primary objective. As the primary environmental factors affecting plant distribution are water and heat processes, hydrologic science must play a critical role in defining system requirements for biodiversity maintenance.

Research Opportunities

In our research we must recognize that the soil is not inert, there is constant interaction with biological organisms that effect soil structure and associated hydrologic response. A portion of our research should be directed towards characterizing biologically mediated changes in soil structure as they relate to hydrologic processes and to develop management practices that optimize positive biological effects and mitigate unwanted biological effects. Validation of complex and interactive models will require simultaneous measurement of biological, soil and atmospheric parameters.

Research to incorporate plant physiological parameters into hydrologic simulation models can take advantage of new methodology that has evolved to practical usage only in the last 5-10 years. Meteorological and soil measurement techniques are generally the most familiar to hydrologic researchers and can usually be monitored remotely with automatic data-acquisition equipment. New methods will have to be used to quantify plant water relations parameters including tissue capacitance, water flux rates, and root growth and development.

Quantification of Plant Water Relations

Incorporation of a dynamic and interactive vegetation component in water balance models requires quantification of the partitioning of water in the plant. There are two general methods to quantify the partitioning of water in plant systems: pressure-volume analysis, following the general principles outlined by Scholander et al. (1964); and the measurement of tissue water potential both before and after cell membrane disruption, following the general principles outlined by Gardner and Ehlig (1965). Modern data acquisition and analysis techniques have made these methods relatively simple to implement with a variety of technical approaches (Hardegree 1989a, Auge et al. 1989, Richter

1978, Ritchie and Roden 1985, Talbot et al. 1975, Wilson et al. 1979, Jones and Turner 1980, Boyer and Potter 1973, Livingston and Black 1987, Cortes and Sinclair 1987, Seeman et al. 1986, Sobrado 1986, Redmann 1976). The plant water relations parameters that can be estimated with these techniques are total water potential, the symplasmic and apoplasmic water volume, the weight-averaged osmotic potential of the symplast at full turgor and at any other hydration state, the weight-averaged turgor pressure of the symplast at any hydration state, and the bulk elastic modulus of the cell walls. Quantification of the plant-water-retention function as it relates to physiological processes is required for true integration of vegetation into hydrologic modeling.

Water Flux Instrumentation

Porometry has been the most widely used method for direct measurement of water flux through individual plants. A current description of available porometry techniques is given by Pearcy et al. (1989). A porometer measures stomatal conductance from which leaf transpiration estimates can be derived. Porometers cannot be used to directly measure leaf transpiration because environmental conditions within the measurement cuvette are very different from those surrounding an open transpiring leaf. Boundary layer conductance, leaf temperature, vapor pressure and wind speed in the canopy all interact to determine actual transpiration for a given level of stomatal conductance. New methods are available, however, for the direct measurement of xylem flow velocity and mass flow of water through stems (Čermák et al. 1973, Sakuratani 1981).

Root System Measurements

Methods for direct observation of root system growth, phenology and rooting density are now available with improvements in minirhizotron technology. A minirhizotron is essentially a root periscope inserted in the soil (Boehm 1974). Recent developments include fiber-optic illumination, and video imaging technology (Richards 1984, Sanders and Brown 1978, Vos and Groenwold 1983, Upchurch and Ritchie 1984) for in situ monitoring of root growth and distribution.

While sampling roots still requires excavation, new technologies are available for quantifying root length and surface area of root samples with video imaging technology. A current description of technology available for root quantification is given by Caldwell and Virginia (1989).

Effects of Soil Faunal Activity on Water and Solute Transport

The effects of soil fauna on soil structure can be readily observed but quantification of these effects remains difficult. One approach to this problem has been to characterize the biological effects on soil porosity using image analysis and computer-assisted tomography. This methodology requires further development before we can use it to relate measured soil properties to hydrologic response. New sampling techniques also need to be developed for measuring subsurface flow in macropores. New methodologies will have to take into account preferential flow patterns in which only a small percentage of the soil volume contributes to flow and where small amounts of solute can move well ahead of the main solute front.

Long-term field studies should be initiated to document the effects of management on biological activity, and the resulting impact on surface and subsurface flow processes. Information from field studies can be used to identify conditions under which biologically mediated changes in soil structure contribute to infiltration rate, chemical movement and sediment loss.

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Scientific Challenges and Opportunities in Wetland and Riparian Research

S.S. Knight[1], P.J. Starks[2], S.P. Hardegree[3], and M.A. Weltz[4]

Summary

Within the last two decades public attitude toward wetland and riparian resources has dramatically changed. These aquatic systems were once viewed as areas to be exploited for agricultural and urban development. Current public perception is that wetland and riparian habitats should be protected and preserved. Because of this change in attitude, and because agriculture can and does have a profound impact on aquatic ecosystems, USDA is faced with the challenge of maintaining the agricultural industry and at the same time protecting these important aquatic resources. Critical gaps in information do exist and must be filled before USDA can meet this challenge. ARS scientist will need to develop evaluation techniques and criteria for the evaluation of resource management, restoration/rehabilitation projects, and assessing ecological damage from off site sources. Future research is needed to further develop restoration and rehabilitation techniques. A better understanding of wetland and riparian hydrology is needed to reduce impact of water diversion, direct water withdrawal or pumping from riparian zones. Not only is this research important in understanding of what hydrological effects physical changes to watersheds might have on wetlands and riparian habitat, but also how do these aquatic habitats affect floodwater storage and abatement. Additional research must be directed toward evaluating what impacts various agricultural practices have on our wetland and riparian resources, particularly the effects of non-point source pollutants such as suspended sediments, excessive nutrients and pesticides.

Introduction

The last 16 years have witnessed a change in public attitude toward aquatic resources. Before this time much of society perceived wetland, swamps and sloughs as obstacles to progress. These inundated lands were useless areas, to be drained and put into valuable agricultural production. They were seen as sources of mosquitoes and insect-borne disease.

Although our rivers and streams were valued by sportsmen and fishermen, public attitude seem to be that these lotic resources were best exploited as conduits for commerce, and waste, and sources for irrigation water. The rich alluvial soils within the riparian zones of rivers and streams were valued more for the agricultural potential than for the ecological role they play in the world around us.

[1] Ecologist, USDA-ARS, P. O. Box 1157, Oxford, MS 38655.
[2] Soil Scientist, USDA-ARS, P. O. Box 1430, Durant, OK 74702.
[3] Plant Physiologist, USDA-ARS, 800 Park Boulevard, Boise, ID 83712.
[4] Hydrologist, USDA, ARS, 2000 East Allen Road, Tucson, AZ 85719.

Attitudes have changed over a surprisingly brief period of time. In 1977, President Jimmy Carter issued Executive Order 11990 protecting wetlands and flood plains. In 1988, Vice-President George Bush made the following statement,

> *"[A]ny nation concerned about the quality of life, now and forever, must be concerned about conservation. It will not be enough to merely halt the damage we've done. Our natural heritage must be recovered and restored....... It's time to renew the environmental ethic in America-and to renew U. S. leadership on environmental issues around the world. Renewal is the way of nature, and it must now become the way of man."*

During the 11 years between these two events the Clean Water Act of 1977, the Food Securities Act of 1985, the Water Resources Development Act of 1986, and the Agricultural Credit Act of 1987 were passed in to law, all of which incorporate some provisions for the protection or restoration of aquatic resources. More recently, the Food, Agriculture, Conservation and Trade Act of 1990 (1990 Farm Bill) contains provisions dealing with delineation, conversion, and restoration of wetlands. Furthermore, the Act establishes a Wetlands Reserve Program, which includes the "set-aside" of riparian zones under certain circumstances (Cohen et al. 1991). Our current Vice-President Al Gore is the author of a best-selling book which expresses his concerns for global ecological health including the loss of aquatic resources.

The study of wetlands and riparian ecosystems is not new; however, most detailed research did not begin until the 1960's (Mitsch and Gosselink 1986). Most early investigations took the form of botanical surveys particularly of coastal marshes (Chapman 1938, 1940; Davis 1940, Teal 1958, 1962; Pomeroy 1959). Other researchers focused on botanical studies of freshwater systems (Cowles 1899, Transeau 1903, Kurz 1928, Dachnowski-Stokes 1935, Lindeman 1942, Gorham 1967). Recent research on wetlands and riparian ecosystems has been more varied and diverse. There have been economic and human value studies (Greeson et al. 1979, Reppert et al. 1979, Larson 1982, Adamus 1983, Sather and Smith 1984), investigation of the hydrologic function of wetland and riparian area, including floodwater storage and abatement (Horton 1914, Novitzki 1979, Verry and Boelter 1979, U.S. Army Corps of Engineers 1972, Gosselink et al. 1981, Ogawa and Male 1983). Several studies on nutrient and sediment dynamics in and through wetlands and riparian areas have been conducted (Klopatek 1978, Simpson et al. 1978, Gambrell and Patrick 1978, Nixon and Lee 1985, Richardson 1985, Kitchens et al. 1975, Odum et al. 1977a, Ewel and Odum 1984, Boyt et al. 1977, Nessel and Bayley 1984, Mitsch et al. 1979, Kuenzler et al. 1980). Webster (1975), Elwood et al. (1983), and Sedell and Froggatt (1984) have studied the "spiral" effects of nutrients downstream in lotic environments. Several researchers have examined the ecological function of wetlands and riparian zones, and their biological productivity (Mitsch and Gosselink 1986, Hammer 1992).

Significant effort has been exerted in an attempt to define or characterize wetlands and riparian zones. Smith (1980) described these aquatic resources as "half-way worlds" between aquatic and terrestrial habitats. Zinn and Copeland (1982) provided two definitions of wetlands, one for scientist and another for managers. They also provided a list of common characteristics that all wetlands share as well as characteristics that make defining distinct boundaries difficult. The U.S. Fish and Wildlife Service has adopted perhaps the most comprehensive definition of wetlands (Cowardin et al. 1979):

Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water ... Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes, (2) the substrate is predominantly undrained hydric soil, and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.

A study by Lefor and Kennard (1977) indicated differences in the definition of wetland were primarily differences in emphasis and depended to a great extent upon the definer's background and training.

The Federal Government's definition is provided by the U.S. Army Corps of Engineers in Section 404 of the 1977 Clean Water Act Amendments. Their definition is given as follows:

The term "wetlands" means those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas. (33 CFR323.2(c); 1984).

Most arguments against this definition involve the period of inundation. Some groups desire a longer period of inundation and others a shorter period of inundation. This definition does not tie wetlands to a particular soil type nor does it specify what plant species or density of plant species must be present.

Since the early 1970's, several authors have presented information on the use of constructed wetlands for the treatment of waste waters, particularly for the removal of nutrient contamination. Hammer (1989, 1992) has published several books and articles devoted to the planning, site selection, design, construction, plant species selection, and operation and maintenance of wetlands constructed for the treatment of waste water. Most constructed wetlands have been employed to remove suspended solids, nutrients, biological oxygen demand (BOD) and bacteria from municipal, industrial or mining waste (Cooper 1989). Marble (1992) provided a guide on how to construct wetlands for various purposes, based upon the U.S. Army Corps of Engineers wetland model called WET. Appendix A supplies a glossary of wetland terms which are used commonly among those working in wetland research. Appendix B lists wetland/native plant suppliers.

Some of the latest research on wetlands and riparian zones is oriented toward developing models. Most of these models concern themselves with habitat assessment and evaluation, some with cumulative effects, while others are more comprehensive such as the WET model mentioned above. (WET evaluates such functions as groundwater recharge and discharge, floodflow alteration, sediment stabilization, sediment/toxicant removal, nutrient removal/transformation, production export, aquatic diversity/abundance, etc.) (The World Wildlife Fund 1992). The U.S. Environmental Protection Agency (1992) evaluated some 21 models for use in water quality research at the watershed scale. These models were evaluated for their potential use in wetland studies as they relate to non-point source pollution and total maximum daily loads (TMDL). Some of the models evaluated, like AGNPS and SWRRBWQ, are probably familiar to those in the USDA.

Agriculture is a major user of water. The U.S. Bureau of the Census (1986) reported that the 20 top irrigation states had a total of more than 42 million acres in irrigation. It was estimated that in 1985 agriculture used about 141 billion gallons of water per day. This represents approximately 41% of all water used in 1985 and a significant portion to the total water available (Solley et al. 1988). Although it is true that about 50% of this water is returned for reuse, it is often laden with pollutants such as sediments, pesticides and nutrients. U.S. Environmental Protection Agency (1990) has reported that non-point sources are responsible for 65% of pollution in degraded streams with 60% of that contamination attributable to agricultural sources (e.g., pesticide and herbicide runoff, sediments, nutrients such as nitrogen and phosphorus, runoff from feed lots).

The agricultural industry is the major user of land in the U.S. and has played a significant role in the destruction of wetlands and riparian habitats. Frey and Hexem (1985) reported that (excluding Alaska) agricultural lands account for 65% of the total land surface or approximately 1.2 billion acres. U.S. Fish and Wildlife Service estimates that 117 million acres of the original 221 million acres of wetlands in the lower 48 states have been lost (Dahl 1990). Twenty-two states have lost 50% or more of their wetlands. Most of these loses (87%) have been attributed to draining for agricultural conversion (Council on Environmental Quality 1989).

Because of the role the agricultural industry had played in the destruction of wetlands and riparian areas and because of the impact agriculture continues to have on aquatic resources, USDA should direct some of its resources toward reducing environmental impact to aquatic ecosystems and restoring or rehabilitating wetlands and riparian zones. The Agricultural Research Service (ARS), the primary research agency within USDA, employs about 2,600 scientists at 122 US locations and seven overseas laboratories. This represents a significant fraction of the national agricultural research capability. Of the $624 million budgeted for FY91 about $77 million were allocated for research on natural resources and the environment including about $29 million for water quality research (Anonymous 1991).

The ARS program plan for 1992-1998 (U.S. Department of Agriculture 1991) included objectives dealing with soil, water, and air conservation and development of new agricultural practices and systems, but was silent on wetland and riparian zone issues. However, in 1991 four agencies within USDA, including ARS, participated in a work shop to identify and develop cross cutting water resources and technology transfer topics that USDA should pursue into the 21st century. One of the four major areas targeted for discussion was wetland and riparian research. Three common or cross-cutting issues concerning wetlands and riparian areas were identified. Vision statements were composed for each issue and major barriers were identified. Recommendations for strengthening interagency cooperation and for the implementation of the vision statements were listed.

Current State of Knowledge

Although the ARS mission includes development of technology needed to insure maintenance of environmental quality and natural resources, ARS remains a relatively small contributor to riparian and wetland research with only seven or eight projects which are directly relevant. Complementary research projects conducted at the Tifton, GA, Beltsville, MD, and University Park, PA, deal primarily with the effects of natural riparian wetlands on hydrology, water quality, and sedimentation. The Oxford, MS, location has two riparian wetland projects. One investigation involves the use of constructed wetlands to treat dairy cattle waste and the other tests effectiveness of four stream rehabilitation measures. Studies in Durant, OK, document sedimentation rates in natural water bodies. Research at Reno, NV, and other western locations focus on impact of

grazing on riparian zone plant communities in watersheds of the semiarid western United States (Shields and Cooper 1992).

Hydrologic Research and Modeling

Although research on riparian and wetland areas per se may number only 7 or 8 projects, there is considerable ARS research being done on upland hydrologic flux of heat and water. The Climate and Hydrologic Systems Element of the ARS Global Change Research Program encompasses research being undertaken by the Northwest Watershed Research Center in Boise, the Hydrology Laboratory in Beltsville, The National Agricultural Water Quality Laboratory in Durant, the Southwest Watershed Research Center in Tucson, the Grassland, Soil and Water Research Laboratory in Temple, and the Great Plains Systems Research Center in Ft. Collins. These locations are all doing research to "Improve predictions of water and energy fluxes to, within and from managed ecosystems by incorporating physically-based components that account for spatial, temporal and scale influences into models." (Global Change, Water Resources and Agriculture, 1992, USDA-ARS, NWRC 92-3; this document presents the Climate and Hydrology Research Component of the Agricultural Research Service Global Change Research Program). The models developed by these research units will be central to understanding water and energy transfer as they relate to streamflow. The Water Research Laboratory in Tifton, GA, is also developing an ecosystem model for the management of riparian areas (Altier et al. in press). This model links riparian processes to upland water input but relies on other models (GLEAMS or NLEAP) for the input.

Coastal Plain Riparian Zone Research

Pionke and Lowrance (1991) found that riparian zones tend to discharge ground water to their associated streams, sometimes providing 50-95% of the stream flow; therefore, riparian processing of nitrogen input from agricultural watersheds is important. Nutrients from agricultural runoff can cause water quality degradation (Lowrance et al. 1985b). Riparian wetlands are sinks for nutrients (due to plant uptake and microbial denitrification) and sediments. Pionke and Lowrance (1991) also found that riparian plant uptake of nitrogen range from 22 to 220 kg N $ha^{-1}yr^{-1}$. Which is in agreement with the range of microbial denitrification in riparian zone soils reported by Gburek et al. (1986) of 0.0007 to 0.0378 g N /M3 /hr which equates to 60-3,000 kg N $ha^{-1}yr^{-1}$. Three ARS investigations, described in greater detail below, have documented nutrient removal from subsurface waters as they pass through riparian wetlands in eastern watersheds.

Lowrance et al. (1983, 1984a) measured water movement and waterborne nutrients for riparian forest ecosystems located in the Little River Watershed and found bottomland hardwood forests were effective sinks for N, P, Ca, Mg, and K. Denitrification capacity could be maintained only if tree harvest was restricted to removal of mature tree and soil disturbance was kept to a minimum (Lowrance et al., 1983, 1984b,c, 1985a). Annual denitrification, found mostly to occur in the top 10 cm of soil, was estimated to be approximately 30 kg N $ha^{-1}yr^{-1}$ (Lowrance et al. 1984c, Hendrickson 1981, Ambus and Lowrance 1991). Riparian zone may also accumulate nutrients in aboveground woody biomass. Lowrance et al. (1984c) and Fail et al. (1986) estimated about 50 kg N $ha^{-1}yr^{-1}$, are stored in the riparian forest of the Little River Watershed. These nutrients can be permanently removed with tree harvest.

Riparian areas are efficient traps of sediments as well as nutrients. Although average erosion rates from cropped lands in the Little River watershed were estimated to be 15,000-20,000 kg $ha^{-1}yr^{-1}$, 99% of this sediment was trapped resulting in relatively low concentrations of sediments in

streamflow (Sheridan et al. 1991). Heede (1991) described similar sediment retention efficiency for vegetated riparian zones in a radically different and western watershed.

Upland Riparian Zone Research

The Northeastern Watershed Research Laboratory has measured water and nutrient movements in ridge and valley watersheds in central Pennsylvania. Land use was 57, 35, and 8% cropland, forest, and pasture, respectively (Schnabel et al. 1990). Although comprising only 2-4% of the watershed, the nearstream zone exerted major controls on streamflow chemistry and hydrology (Pionke et al. 1988). Stream nitrate concentrations were found to be dependent on the amounts of surface runoff, groundwater inflow, and rainfall present. Each of these contributors to streamflow were found to have different concentrations of nutrients. Schnabel (1986) and Schnabel et al. (1990) found that shallow groundwater contributed a greater proportion to streamflow following storm events. Based on this information Pionke et al. (1988) developed a conceptual model of near-stream zone hydrology.

Western Montane Riparian Zones Research

The Landscape Ecology of Rangelands Research Laboratory has investigated the effects of cattle grazing on plant communities and water and nutrient movements in northern Sierra Nevada montane meadows. Grazing was found to have virtually no effect on water table, soil redox potential, and shallow ground water nitrogen concentration in these N-limited meadows (Riegel et al. 1991b). Plant community composition, vegetative growth (Riegel et al. 1990, 1991a; Svejcar et al. 1991), and root densities (Manning et al. 1989), were primarily dependent on water table depth. Successful establishment of shrubby willows (*Salix geyeriana* and *S. lemmonii*) (Conroy and Svejcar 1991, Svejcar et al. 1991) was also dependent upon depth of water table. Lowering of water table depth due to channel downcutting could severely impact plant physiology and production.

Estuarine Buffer Zone Research

Parken et al. (1988) of the Environmental Chemistry Laboratory conducted research which examined the removal of nitrate from groundwater moving from soybean fields through a grass buffer strip, a forest and a marsh before the Wye River, a tidal river tributary to Chesapeake Bay. Comis (1990) reported nitrate declined most rapidly during winter while plants are dormant, indicating denitrification as a mechanism for nutrient removal. Research is complicated by the variable hydrology of the site which changes seasonally due to tidal influence (Parken et al. 1988).

Riparian Zone Restoration

Bowie (1982) and Grissinger and Bowie (1982), at the National Sedimentation Laboratory, studied the use of riparian vegetation and structural materials to control stream bank erosion as well as channel-riparian zone vegetation interactions. Shields et al. (in press) have developed aquatic habitat restoration techniques for unstable, agricultural channels using native black willow (*Salix nigra*) in combination with stone to promote improved habitat for fish and macroinvertebrates at base flow. A 1.5 ha riparian forest along with a first-order stream channel has been restored with native tree species including yellow poplar (*Liriodendron tulipifera L.*), green ash (*Fraxinus pennsylvanica* var *biflora* (Walt.) Sarg.), and slash pine (*Pinus elliotti* Engelm.) and will be treated with liquid dairy waste to examine nutrient movement and uptake by a restored riparian forest.

Constructed Wetlands

Researchers at the National Sedimentation Laboratory in cooperation with the SCS built a constructed wetland for the treatment of dairy farm waste in northwestern Mississippi. Waste water from an anaerobic lagoon was gravity fed to 20 ft. by 80 ft. wetland cells planted in giant

bulrush (*Scirpus validus*). Cooper et al. (1993) measured calculated reductions in fecal coliform, ammonia, chlorophyll and BOD of 96%, 91%, 77%, and 70%, respectively. Filterable ortho-phosphate and total phosphorus were reduced by 57% and 70%, respectively, using a constructed wetland to treat dairy cattle waste.

Scientific Challenges

A seemingly simple, but necessary challenge that faces ARS researchers is in defining what is or what is not a wetland or riparian zone. Although several authors have attempted to define these ecosystems, there is no agreement on definition among scientist, managers, or lawmakers (Smith 1980, Zinn and Copeland 1982, Lefor and Kennard 1977). Perhaps the most widely accepted and most comprehensive definition of wetland is the one adopted by the U.S. Fish and Wildlife Service (Cowardin et al. 1979). Riparian habitat is even more difficult to define or delineate. This is a difficult issue to resolve because of the indefinite character of wetlands and riparian zones. These habitats are ectones between dry land and deep water. Before research goals can be established or results can be coordinated, a common language must be developed. Although, some researchers and resource managers are delineating wetlands, as ARS scientists we must decide if their definition is sufficient to meet our research needs? Other related issues that should be addressed are: "Do we have adequate technology to delineate aquatic resources? Can we use remote-sensed data to delineate wetlands and riparian areas? How do you define the boundaries of a wetland or riparian area? What information do we need to define these environments."

A cross-cutting issue concerning wetlands and riparian zones identified during the USDA Water Resource Research and Technology Transfer Workshop was the need to help managers set a clear goals for wetland/riparian management. Goals should address society's needs and yet be practical enough to allow for a reasonable chance of success. Scientific challenges that face ARS researchers include testing various management strategies so the reasonable estimation of success might be extrapolated to different resources through out the United States.

Often the success or failure of an environmental management strategy is "in the eyes of the beholder." For example what might meet SCS needs might not be acceptable to EPA. A critical question that must be answered is "How do we evaluate wetlands/riparian resources and management strategies?" An agreed upon standard of measurement will be required. This standard might use biological criteria such as species diversity, community composition, or productivity, or may incorporate hydrological, chemical, or physical characteristics or some combination. A possible solution might entail the identification of references resources so that researchers and managers alike would have a "yard stick" by which to measure successful management or technology. Related challenges include measuring functional value of wetlands and riparian zones, evaluating wetlands and riparian zones while taking into account tremendous natural variability within these systems and developing a fundamental understanding of wetland/riparian resource function in time and space.

A third major challenge that must be addressed by the ARS scientist is evaluating what impacts various agricultural practices have on our wetland/riparian resources. Further research is need to determine the effects of water borne pollutants such as excessive nutrients, sediment and pesticides and metals on wetlands and riparian areas. Additional research is needed to evaluate the effects of grazing on riparian habitats, particularly in the arid western states. More information is needed to fully understand the hydrologic function of wetlands and riparian zone. Not only is research needed to understand what hydrological effects channelization, levee construction and regulation of flood

regime has on these resources, but also how do these aquatic habitats affect floodwater storage and abatement. Other hydrology related issues include the impact of water diversion, direct water withdrawal or pumping from riparian zones on these aquatic resources. One of our greatest current challenges will be to more directly relate riparian and wetland processes to the upland hydrologic events that ultimately drive in-stream availability of water. These upland events will determine the spatial and temporal variability, of water in riparian/wetland areas and, therefore, processes associated with water quality and instream plant and animal life.

A related scientific challenge addressed in the USDA Water Resource Research and Technology Transfer Workshop included developing ways of protecting these ecosystems in a way that is sensitive to agricultural needs and formulating repair strategies such as restoration or rehabilitation for damaged ecosystems. Further research is needed to develop restoration/rehabilitation methods that are based on hydrologic manipulation and/or re-vegetation. Key plant species that exert the greatest influence on success or failure of a restoration or rehabilitation project should be identified. Adequate sources of this material must be located. ARS research may develop these plant materials as a new agricultural product.

The fourth scientific challenge addressed in the USDA Water Resource Research and Technology Transfer Workshop included issues of scale. Most research, management and restoration/rehabilitation efforts have been on small scale "manageable size" locations such as subwatersheds, 1 km stream reaches, or 0.1 ha wetland cells. Although "do-able," small scale projects are not always applicable or suitable for answering questions in a landscape context. Integrated aquatic ecosystem restoration also requires a broader approach that include linking wetland/riparian processes to upstream and downstream features. ARS scientists must first determine what is the most effective scale at which the most significant improvements in habitat quality can be made.

Research Opportunities

ARS should direct some research efforts in developing new technology to delineate aquatic resources. Techniques using remote sensed data and geographical information systems (GIS) to delineate wetlands and riparian areas should be developed.

ARS scientist should develop evaluation techniques and criteria for the evaluation of resource management, restoration/rehabilitation projects, and assessing ecological damage from off site sources. Research should identify reference resources as a standard by which to measure successful management or technology. A fundamental understanding of wetland/riparian resource function in time and space would aid ARS research in measuring functional value of wetlands and riparian zones and in evaluating wetlands and riparian zones while taking into account tremendous natural variability within these systems. More information is needed to fully understand the hydrologic function of wetlands and riparian zones. Not only is this research important in understanding of what hydrological effects physical changes to watersheds might have on wetlands and riparian habitat, but also how do these aquatic habitats affect floodwater storage and abatement.

ARS researchers should test various resource management strategies so that better alternatives may be passed on the managers. Better management strategies may reduce the effects of grazing on riparian habitats, particularly in the arid western states. Hydrology research could provide information needed by resource managers to reduce impact of water diversion, direct water withdrawal or pumping from riparian zones.

Research is needed to evaluate what impacts various agricultural practices have on our wetland/riparian resources. Further research is need to determine the effects of non-point source pollutants such as suspended sediments, excessive nutrients and pesticides on wetlands and riparian areas.

To date no wetland restoration project has recreated a fully functional wetland that has maintained regional biodiversity (Committee on Restoration of Aquatic Ecosystems: Science, Technology and Public Policy, 1992). Further research is needed to develop restoration/rehabilitation methods that can recreate fully functional wetlands, at the most effective scale to provide the most significant improvements in habitat quality.

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Biographical Information

Carlos Alonso

Education: PhD Fluid Mechanics; Hydraulics, University of Iowa

Experience:

1972-Present USDA-ARS, Ft. Collins, CO, Hydraulic Engineer.

Jeffrey Arnold

Education:

PhD	Agricultural Engineering; Spatial scale variability in model development and parameterization, Purdue University
MS	Agricultural Engineering; Soil and Water, University of Illinois
BS	Agricultural Engineering; Soil and Water Conservation, University of Illinois

Experience:

1992-Present USDA-ARS, Temple, TX, Agricultural Engineer. Development of river-basin scale models and linking GIS with models and large area data bases.

1989-92 USDA-ARS, West Lafayette, IN. WEPP crop growth simulation.

1983-89 USDA-ARS, Temple, TX. Development of watershed scale simulation models.

Wilbert Blackburn

Education:

PhD	Hydrology, University of Nevada, Reno
MS	Range Science, University of Nevada, Reno
BS	Botany-Range Management (Minor: Agronomy), Brigham Young University

Experience:

1992-Present USDA-ARS, Ft. Collins, CO, Senior Executive Service, Northern Plains Area, Associate Area Director.

1987-92 USDA-ARS, Boise, ID, Supervisory Research Hydrologist, Research Leader, Location Coordinator.

1975-87 Associate Professor/Professor of Watershed Management, Texas A&M University, College Station.

1965-75 Graduate Research Assistant/Instructor and Range Ecologist/Assistant Professor of Watershed Management, University of Nevada, Reno.

Jim Bonta

Education:	PhD	Civil Engineering; Hydrology and Hydraulics, Purdue University
	MS	Civil Engineering; Hydrology and Hydraulics, Ohio State University
	BS	Watershed Science, Utah State University

Experience:

1975-Present	USDA-ARS, Coshocton, OH, Hydraulic Engineer. Studying impacts of surface mining for coal on hydrology and water quality; flood hydrology, precipitation characterization, erosion, and groundwater hydrology and water quality.

David Bosch

Education:	PhD	Hydrology, University of Arizona
	MS	Agricultural Engineering, University of Minnesota
	BS	Agricultural Engineering, University of Minnesota

Experience:

1990-Present	USDA-ARS, Tifton, GA, Research Hydrologist. Adjunct Research Associate, Department of Biological and Agricultural Engineering, University of Georgia. Research Interests include: developing solute transport models for predicting movement of water soluble chemicals and soil moisture in variably saturated soils, and developing new methods for assessing the impact agricultural chemicals on ground and surface water supplies.
1986-90	USDA-ARS, Tucson, AZ, Graduate Research Associate.

Doug Boyer

Education:	PhD	Forest Hydrology, West Virginia University
	MS	Forest Hydrology, West Virginia University
	BS	Forest Resources Management, West Virginia University

Experience:

1979-Present	USDA-ARS, Beckley, WV, Hydrologist. Topographic effects on pasture microclimatology in steep terrain. Agricultural impacts on groundwater quality in karst terrain.

John Daniel

Education:	PhD	Geology; Sedimentology, South Dakota School of Mines and Technology
	MS	Geochemistry; Organic Geochemistry, Montana College of Mineral Science and Technology
	BS	Geology, University of Kansas

Experience:

1992-Present	USDA-ARS, Durant, OK, Geologist. Animal waste management, GW quality and GW recharge.
1990-92	USDA-ARS, Morris, MN, Post doctoral Soil Scientist. Depressional focused recharge.
1988-90	Instructor of Geology, University of Minnesota-Morris.
1978-84	Graduate Student/Geologist at Montana Bureau of Mines and Geology. Mineral fuels resource evaluation.

David Farrell

Education:	PhD	Irrigation; Agricultural Engineering, University of Melbourne, Victoria, Australia
	BCE	Civil Engineering, University of Melbourne, Victoria, Australia

Experience:

1975-Present	USDA-ARS, Beltsville, MD, National Program Leader for Hydrology, National Program Staff.
1973-75	Senior Principal Research Scientist, Division of Soils, Commonwealth Scientific and Industrial Research Organization (CSIRO), Adelaide, South Australia, Australia.
1969-73	USDA-ARS, St. Paul, MN, Supervisory Soil Scientist. Professor of Soil Mechanics, Department of Soil Science, University of Minnesota.
1968-69	Senior Research Scientist, Division of Soils, CSIRO, Adelaide, South Australia, Australia.
1966-68	Visiting Lecturer, Department of Agronomy, Iowa State University, Ames.
1963-66	Research Scientist, Division of Soils, CSIRO, Adelaide, South Australia, Australia.
1962-63	Lecturer, Department of Agricultural Engineering, University of Melbourne, Victoria, Australia.
1959-60	Research Officer, Department of Agricultural Engineering, University of Melbourne, Victoria, Australia.
1955-59	Civil Engineer (Hydraulics), Commonwealth Department of Works, Hawthorn, Victoria, Australia.

Charlie Feldhake

Education:	PhD	Soil-Plant-Water Relations, Colorado State University
	MS	Colorado State University
	BS	Xavier University

Experience:

1981-Present USDA-ARS, Beckley, WV, Soil Scientist. Plant canopy energy budgets. Effect of topography on pasture microclimate. Agro forestry.

Glenn Fernandez

Education:	PhD	Agricultural Engineering, Louisiana State University
	MS	Agricultural Engineering, University of the Philippines in Los Banos
	BS	Agricultural Engineering, University of the Philippines in Los Banos

Experience:

1992-Present USDA-ARS, Durant, OK, Post doctoral research. Research on impact of climate fluctuations on watershed runoff.

1980-92 Instructor, Assistant Professor of Agricultural Engineering and Agricultural Meteorology, College of Engineering and Agro-Industrial Technology. University of the Philippines at Los Banos College, Laguna, Philippines.

Virginia Ferreira

Education:	MS	Hydrology, Colorado State University
	BS	Mathematics, University of Arizona

Experience:

1993-Present USDA-ARS, Fort Collins, CO, Mathematician, TERRA Laboratory

1984-93 USDA-ARS, Fort Collins, CO, Mathematician, Hydro-Ecosystems Research Group and Great Plains Systems Research Unit.

1981-83 USDA-ARS, Tifton, GA, Mathematician.

1970-80 USDA-ARS, Tucson, AZ, Hydrologic Technician.

Gerald Flerchinger

Education:	PhD	Engineering Science, Agricultural Engineering: Simultaneous Heat and Water Model of a Snow-Residue-Soil System, Washington State University
	MS	Civil Engineering; Predicting Infiltration for ROSED a Road Sediment Model, University of Idaho
	BS	Agricultural Engineering, Emphasis: Soil and Water Resources, University of Idaho

Experience:

1988-Present USDA-ARS, Boise, ID, Hydraulic Engineer. Research includes modeling transpiration, soil freezing and spatial and temporal variability of soil heat and water in relation to plant cover. Currently conducting research on groundwater flow in steep mountainous slopes and solute transport and pesticide movement from hazardous waste sites.

1984-88 USDA-ARS, Pullman, WA. Performed research toward the solution of water management and erosion prevention where snow melt and frozen soul create significant management problems. Developed new technology, the SHAW model, for predicting the effects of residue and tillage management on soil freezing and evaporation.

1982-84 Civil Engineering Department, University of Idaho, Moscow. Conducted research on runoff and erosion from forest roads using rainfall simulator. Modified and applied a model which simulates runoff and erosion from a road prism. Developed methodology to predict infiltration parameters of road surfaces and cut slopes.

Jurgen Garbrecht

Education:	PhD	Hydrology; Channel water and sediment routing, Colorado State University
	MS	Hydraulics; Physical basis of stream flow hydrology, Colorado State University

Experience:

Present USDA-ARS, Durant, OK, Hydraulic Engineer. Physical process based numerical modeling of event type and continuous rainfall-runoff hydrology in large watersheds, including channel flow routing, sediment transport and water quality modeling in complex channel networks.

David Goodrich

Education:

PhD	Hydrology and Water Research; Scale and Complexity in Rainfall-Runoff Models, University of Arizona
MS	Civil and Environmental Engineering; Close Range Photogrammetry/Hydrologic Modeling, University of Wisconsin
CPGS	Control Engineering; Hydrologic Time Series Modeling, Cambridge University
BS	Civil and Environmental Engineering; Hydrology/ Photogrammetry, University of Wisconsin

Experience:

1988-Present — USDA-ARS, Tucson, AZ, Research Hydraulic Engineer. Scaling issues in rainfall-runoff modeling, identification of dominant hydrologic processes over a range of basin scale, climatic change impacts on semiarid hydrologic processes over a range of basin scale, climatic change impacts on semiarid hydrologic response and incorporation of remotely sensed data into hydrologic modeling using geographic information systems.

Pre-1988 — Consulting Scientist, Autometric Inc, Falls Church, VA. Image analysis and positioning with satellite imagery. Water Resource Division of the USGS in Alaska and Wisconsin. Surface and groundwater quantity measurements, analysis and reduction of data, and flood routing analysis for flood insurance studies. Independent research investigations were also carried out with the Canadian Exploration Group to acquire basic data in remote areas of British Columbia.

Stuart Hardegree

Education:

PhD	Soil Science; Wildland Resource Science Plant Physiology, University of California, Berkeley
MS	Soil Science; Wildland Resource Science Plant Physiology, University of California, Berkeley
BS	Forestry; Rangeland Management, University of California, Berkeley

Experience:

Present — USDA-ARS, Boise ID, Plant Physiologist. Research interests include physiological ecology of rangeland species, plant and soil water relations, plant establishment and rehabilitation of disturbed lands.

Karen Humes

Education:

PhD	Hydrology (minor: Remote Sensing); Estimation and scaling of surface energy balance components with remotely-sensed data.
MS	Soil and Water Science: Soil roughness effects on soil spectral reflectance, University of Arizona
BS	Geophysics, New Mexico Institute of Mining and Technology

Experience:

1992-Present USDA-ARS, Beltsville, MD, Research Physical Scientist. Research topics include the analysis of ground-based and remotely-sensed data from several multidisciplinary field experiments (MONSOON '90 First ISLSCP Field Experiment, NASA European Multi-Aircraft Campaign, HAPEX-Sahel) to quantify spatially distributed land-surface energy fluxes and land-surface/atmosphere interaction.

1988-91 NASA Graduate Student Research Fellow, Department of Hydrology and Water Resources, University of Arizona. Cooperative research with Hydrological Sciences Branch, NASA Goddard Space Flight Center, in the area of estimating and modeling the energy and moisture fluxes at the land surface and upper soil profile with remotely-sensed data.

1984-88 Graduate Research Associate and Teaching Assistant, Department of Soil and Water Science, University of Arizona. Duties included processing, analysis and interpretation of ground-based and satellite-based remotely sensed data for remote sensing applications in soil and water science; teaching and grading for 5 sections of Basic Soil Science Laboratory, and assisting with exams and grading for a course in Soil Physics.

1979-84 Engineer, NASA Jet Propulsion Laboratory, California Institute of Technology. Analysis of space-based geodetic measurements from Very Long Baseline Interferometric systems for applications in geophysics and spacecraft tracking; Technical Group Leader, 1983-84.

Greg Johnson

Education:

PhD	Atmospheric Science; Urban temperature bias estimated from satellite, North Carolina State University
MS	Meteorology, University of Wisconsin
BS	Atmospheric Science, Oregon State University

Experience:

1991-Present USDA-ARS, Boise, ID, Research Meteorologist. Climatic variability, especially at watershed scale, and as related to land surface characteristics and large-scale meteorology.

1979-91 Agricultural Meteorology, North Carolina State University, Extension Service. Applied research of weather forecast applications to pest and disease management; drought; frost and freeze probabilities and mitigation.

Scott Knight

Education:	PhD	Fisheries Management; Statistical survey design, Ecology of warm water fishes, Fish population dynamics, Auburn University
	MS	Wildlife Management; Fisheries management, Food habits of warm water fishes, Effects of flooding on riverine fishes, Mississippi State University
	BS	Zoology, University of Mississippi

Experience:

1986-Present	USDA-ARS, Oxford, MS, Ecologist. Current research interest include the use of constructed wetlands to manage dairy waste, and stream habitat restoration.
1984-86	USDA-ARS, post-doctoral. Evaluated the environmental impact of erosion control construction on aquatic ecosystems. Studied nutrient and sediment trapping efficiency of farm ponds, water quality of bluffline streams and evaluated the fish habitat value of stream bank erosion control measures.
Pre-1984	U.S. Army Corps of Engineering, Waterways Experiment Station. Aquatics Habitat Group to conduct research on the biology, food habits, and habitat selection of Mississippi River fishes.

Bill Kustas

Education:	PhD	Hydrology, Cornell University
	MS	Hydrology, Cornell University
	BS	Forest Engineering, State University of New York, College of Environmental Science and Forestry

Experience:

1986-Present	USDA-ARS, Beltsville, MD, Hydrologist. Quantifying energy fluxes from field to basin scales with remote sensing.

Mary Moran

Education:

PhD	Soil and Water Science; Satellite-based Approach for Evaluation of the Spatial Distribution of Evapotranspiration from Agricultural Lands, University of Arizona
MS	Geography; Modeling Timber Site Suitability through the Use of Digital Terrain Tapes, Lands at Data and Soils Maps, University of California
BS	Geography, University of California

Experience:

1992-Present Adjunct Professor, Department of Soil and Water Science, University of Arizona, Tucson.

1984-Present USDA-ARS, Phoenix, AZ, Physical Scientist.

1983-84 Programmer/Analyst, Dynacomp, Inc., Phoenix, AZ.

1982-83 Research Project Manager, Office of Arid Lands Studies, Tucson, AZ.

1980-82 Graduate Research Assistant and Teaching Assistant, Department of Geography, University of California, Santa Barbara.

1976-80 Biological Research Technician, National Park Service, Grand Canyon, AZ.

Lloyd Owens

Education:

PhD	Agronomy; Soil Chemistry, Purdue University
MS	Agronomy; Soil Biochemistry; Purdue University
	Agriculture (Soil Balance Fellow); Pedology, University of Rhodesia
BS	History Education, Purdue University

Experience:

1976-Present USDA-ARS, Coshocton, OH, Research Leader. Research experience includes studying the processes of nitrogen movement in surface runoff, on sediment, through the soil profile, and in subsurface flow; investigating factors which influence these processes; and bringing the different parts together in context of watershed systems. Agricultural management variables studied in pasture systems included (1) nitrogen fertilization levels, (2) timeliness of nitrogen application, (3) nitrogen forms and release rates, (4) use of legumes instead of commercial nitrogen. Also management variables in corn/soybean rotation have (are) been studied with no-till and chisel plow practices on small watersheds and large, monolith lysimeters.

Frederick Pierson

Education:	PhD	Soil Physics, Washington State University
	MS	Range Management, Washington State University
	BS	Range Management, Humbolt State University

Experience:

1988-Present	USDA-ARS, Boise, ID, Research Hydrologist.
1985-1988	Graduate Research Assistant, Department of Agronomy and Soils, Washington State University, Teaching Assistant.
1983-85	Graduate Research Assistant, Forest and Range Management Department, Washington State University.
1982	Range Aid, U.S. Forest Service, El Dorado National Forest.

Harry Pionke

Education:	PhD	Soil Science, Chemistry; Developing analytical methodology for chlorinated hydrocarbon insecticides in soils and waters, University of Wisconsin
	MS	Soil Science; Evaluating lime requirement tests on Wisconsin soils, University of Wisconsin
	BS	Soil Science; Agricultural Economics, University of Wisconsin

Experience:

1992-Present	USDA-ARS, University Park, PA, Research Leader. Developing methods to chemically validate hydrologic models to better explain the groundwater and streamflow responses observed at the water shed scale, and to better delineate groundwater discharge and surface runoff zones. Developed a unique sampling and specialized tracing technologies using stable isotopes an geochemicals to validate hydrologically based simulations at the larger spatial scales.
1980-92	Researched the impact of agricultural land use on water quality at a watershed scale; particularly the nitrate contents in groundwater and streamflow, similar research with pesticides and phosphorus.
1975-80	Researched focused on controlling the quality of leachate from coal strip mine spoil.
1974-75	USDA-ARS, University Park, PA, Research Leader.
1968-74	Defined critical watershed and impoundment characteristics affecting salinity of streamflow and impounded waters.
1967-68	Assistant Professor of Soils, Soils Department, University of Wisconsin.

Albert Rango

Education:	PhD	Watershed Management; Effects of weather modification, Colorado State University
	MS	Meteorology; Hydrometeorology, Pennsylvania State University
	BS	Meteorology, Pennsylvania State University

Experience:

1983-Present	USDA-ARS, Beltsville, MD, Research Leader.
1972-83	NASA Goddard Space Flight Center, Hydrological Science Branch.
1969-72	Department of Meteorology, Pennsylvania State University.

Clarence Richardson

Education:	PhD	Civil Engineering, Colorado State University
	MS	Agricultural Engineering, Texas A&M University
	BS	Agricultural Engineering, Texas A&M University

Experience:

1987-Present	USDA-ARS, Temple, TX, Laboratory Director, Research Leader, and Agricultural Engineer. Leadership of a multi-disciplinary research program.
1980-87	USDA-ARS, Temple, TX, Research Leader and Agricultural Engineer. Hydrology research and leadership of soil and water research.
1972-80	USDA-ARS, Temple, TX, Agricultural Engineer. Hydrology and weather simulation research.
1966-72	USDA-ARS, Riesel, TX, Agricultural Engineer. Hydrology and erosion research.
1965-66	Instructor, Agricultural Engineering Department, Texas A&M University, College Station. Instructor of agricultural engineering courses.
1964-65	Research Technician, Texas Agricultural Experiment Station, Riesel, TX. Research Assistant for hydrology research.

Frank Schiebe

Education:	PhD	Civil Engineering; Hydraulics and Water Resources (minor, Public Health; Environmental Aquatic Biology), University of Minnesota
	MS	Civil Engineering, Hydromechanics (minor, Electrical Engineering; Acoustics), University of Minnesota
	BS	Electronics (minor, Electric Power Systems), University of Minnesota

Experience:

1983-Present USDA-ARS, Durant, OK, Laboratory Director/Research Hydraulic Engineer.

1980-83 USDA-ARS, Durant/Chickasha, OK, Research Leader/Research Hydraulic Engineer.

1976-80 USDA-ARS, Oxford, MS, Hydraulic Engineer.

1965-73 Senior Scientist, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

1964-65 Scientist, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

1960-64 Associate Scientist, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

1957-60 Assistant Scientist, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Jan van Schilfgaarde

Education:	PhD	Agricultural Engineering and Soil Physics, Iowa State University
	MS	Agricultural Engineering, Iowa State University
	BS	Agricultural Engineering, Iowa State University

Experience:

1991-Present USDA-ARS, Beltsville, MD, Associate Deputy Administrator, Natural Resource and Systems, National Program Staff.

1984-91 USDA-ARS, Ft. Collins, CO, Associate Director of the Northern Plains Area. Director of Mountain States Area, Fort Collins, CO. Responsible for agency's research program in eight states.

1972-84 USDA-ARS, Riverside, CA, Director. Irrigation water management and salinity problems with water quality of the Colorado River System.

1971-72 Director of the Division of Water Management. Planning, coordinating, and directing national program of research in fields of water management, watershed engineering, and soil management.

1967-71 Associate Director of Water Management.

1964-67 Chief Water Management Engineer, Soil and Water Conservation Research Division, ARS (SWC). Technical coordination of water management across the nation.

1954-64 Assistant Professor, Associate Professor and Professor of Agricultural Engineering, as well as, USDA-ARS Agent; drainage engineer, Raleigh, NC.

Ron Schnabel

Education:	PhD	Soil Science; Nitrate leaching from furrow irrigated soils, Washington State University
	MS	Soil Science, South Dakota State University
	BS	Environmental Management, South Dakota State University

Experience:

1991-Present	USDA-ARS, University Park, PA, Research Soil Scientist. Riparian zone impact on nitrogen export from watersheds.
1980-91	USDA-ARS, Northeast Watershed Research Center, Research Soil Scientist. Nitrogen leaching and chemical retention by soil.

Mark Seyfried

Education:	PhD	Soil Physics, University of Florida
	MS	Soil Genesis and Classification, University of Florida
	BS	Soil Research Management, University of California

Experience:

1988-Present	USDA-ARS, Boise, ID, Soil Scientist. Infiltration into and runoff from frozen soil, spatial variability of soil moisture on a watershed scale, remote sensing of soil moisture and frost, and quantitative description of ground water recharge from snow pack.
1988	Post doctoral research, University of Delaware. Developed the methodology on mathematical description of the kinetics of cation exchange on soil.
1986-88	Post doctoral research, University of Florida. Evaluated soil classification for describing the variability of soil properties related to pesticide movement; evaluated pesticide leaching models.
1983-86	Research Assistant, Soil Science Department, University of Florida. Developed model describing field data collected in Costa Rica; conducted two related studies: one concerned with preferential flow in Costa Rican soils, the other with rates of nitrogen mineralization.
1982-83	Scientist, CATIE (Centro Agronomico Tropical de Investigaciones y Ensenaza) in Costa Rica. Field measurement of soil water and nutrient movement under different cropping systems (part of doctoral program).
1980-82	Research Assistant, University of Florida. Investigated productivity of soils in citrus growing region with particular emphasis on water relations.
1977-80	USDA-SCS, Soil Scientist. Primary responsibility was mapping soils. Designed mapping units and proposed new soil series.

Martin Shipitalo

Education:	PhD	Soil Science; Effects of Earthworms and Tillage on Soil Structure, University of Guelph
	MS	Soil Science; Soil Genesis, Ohio State University
	BS	Agronomy, Ohio State University

Experience:

1989-Present	USDA-ARS, Coshocton, OH, Soil Scientist. Effects of conservation tillage on surface and subsurface water quality. Primary research emphasis is on how biologically mediated changes in soil structure affect the movement of surface-applied chemicals through the soil in macropores.
1986-89	USDA-ARS, Coshocton, OH, Post doctoral research associate.

Patrick Starks

Education:	PhD	Agronomy; Micrometeorology/"Measured and Modeled Radiation Fluxes at the Fife Site", University of Nebraska
	MS	Physical Geography; Remote Sensing/"Analysis of the Rain basin Depressions of Clay, Clay County, Nebraska", University of Nebraska
	BS	Physical Geography, University of Central Arkansas

Experience:

1992-Present	USDA-ARS, Durant, OK, Soil Scientist. Calibrating (wavelength, radiometric, temperature) hyper spectral remote sensing instrumentation. Began a wetland research study in terms of identification and delineation. Sedimentation studies, fate and transport of agricultural chemicals into/through wetland ecosystems.

Adrian Thomas

Education:	PhD	Agricultural Engineering, Colorado State University
	MS	Agricultural Engineering, Clemson University
	BS	Agricultural Engineering, Clemson University

Experience:

1989-Present	USDA-ARS, Tifton, GA, Laboratory Director and Research Leader. Current objectives: to develop and test aerial and close-range photogrammetric techniques for quantifying soil erosion and parameters that affect soil erosion; to develop and test methodologies for predicting ephemeral gully erosion; to develop and test model structures for incorporating seasonal risk and variability of climate in management options to facilitate conservation, production, and environmental planning; and to characterize and quantify climatic parameters that affect the management of soil and water resources.

Clinton Truman

Education:

PhD	Agronomy; Soil Physics, Purdue University
MS	Agronomy; Soil Classification and Morphology, University of Georgia
BS	Agronomy; Soils, University of Georgia

Experience:

1991-Present USDA-ARS, Tifton, GA, Soil Scientist. Adjunct Research Associate, Department of Agronomy, University of Georgia. Research includes conducting field and laboratory studies to define and quantify physical and chemical processes and mechanisms controlling behavior, transport, and fate of agrochemical in soils, sediment, and surface and groundwater. Current research includes: develop/evaluate ground penetrating radar and other geophysical methods for non-destructive characterization of soil and subsurface features affecting water and solute transport rates and pathways; investigate agrochemical partitioning and entrainment between and into infiltration, runoff, and subsurface lateral flow, over a range of agrochemical properties, uses, and rainfall patterns; classify soil according to soil-pesticide interactions into group relating potential agrochemical contamination to runoff and subsurface water; evaluate existing root-zone models such as GLEAMS, assessment technologies, and model-based decision-aids for water quality management.

1990-91 USDA-ARS, Tifton, GA, Post-Doctoral Research Associate. Evaluated model representation of processes controlling nutrient cycling and transport; modified the GLEAMS model to simulate nutrient transport processes; evaluated rational of GLEAMS for linking its nutrient, hydrology, soil erosion, and pesticide components; and evaluated GLEAMS' utility in selecting management practices and development of decision-aids.

1986-90 USDA-ARS, West Lafayette, IN. Agronomy Department, Purdue University, Graduate Research Assistant. Conducted field and laboratory research on interrill erosion mechanics. Other research included erosion mechanics-the role of soil structural stability in interrill erosion processes.

1985-86 Department of Agronomy, University of Georgia, Graduate Research Assistant. Conducted field research to determine the capability of ground-penetrating radar in agricultural soils. Other research included the role of surface sealing/crusting on seedling emergence, infiltration, and soil loss.

Mark Weltz

Education:

PhD	Range Watershed; Observed and estimated (ERHYM-II model) water budgets for south Texas rangelands, Texas A&M University
MS	Range Watershed; The influence of short duration and continuous grazing on infiltration rate and sediment yield in south-central New Mexico, New Mexico State University
BS	Range Science, Humbolt State University

Experience:

1987-Present Erosion indicator lead for Environmental Protection Agency Environmental Monitoring and Assessment Program (EMAP). Researcher and Core Team member on the USDA Water Erosion Prediction Project (WEPP). Responsibilities are to develop the algorithms and model subroutines to predict the influence of changes in vegetation and ground surface cover on runoff and erosion rates. Develop methodologies to represent the influence of management practices (e.g. burning, herbicides, and grazing) on runoff and erosion rates. Developed methodology to estimate leaf area index of native trees, shrubs, and grasses. Developed methodology to estimate hydraulic roughness on rangelands. Conducted field experiments with rainfall simulator in 10 western states at 22 locations to develop relational database to validate WEPP, RUSLE and other hydrologic and erosion simulation models. Developed and installed 9 non-weighing lysimeters for determining water budgets of native plant communities.

Ross Wight

Education:

PhD	Range Science; Site vegetation characteristics and relationships of juniper communities, University of Wyoming
MS	Soils; Development and evaluation of laboratory methods for determining the nitrogen supplying power of irrigated soils of northern Utah, Utah State University
BS	Soil Conservation, Utah State University

Experience:

1978-Present USDA-ARS, Boise, ID, Range Scientist. Major emphasis on the development and application of rangeland models. Research activities consist of: 1) field research and soil-climate-plant relationships, 2) Continued development, testing, and application of ERHYM (Ekalaka Rangeland Hydrology and Yield Model), and 3) coordinator of the ARS SPUR modeling project.

1965-80 USDA-ARS, Sidney, MT, Range Scientist. Research focused on the identification and quantification of yield-limiting factors and the development of management practices to reduce their effects. University State University, for training and experience in system analysis and modeling technology.

1963-65 Research Assistant and Computer Programmer, University of Wyoming.

1958-63 Laboratory Technician II, University of California.

1956-58 USDA-SCS, Logan, UT, Soil Testing Laboratory.

1954-56 Served as an officer in the U.S. Ordinance Corps in Germany.

1950-54 USDA-SCS, Logan, UT, Soil Testing Laboratory.

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